高時間分解能検出器(LGAD)の細密電極化に関する開発

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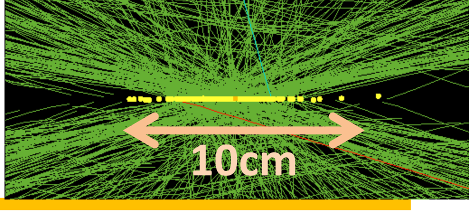
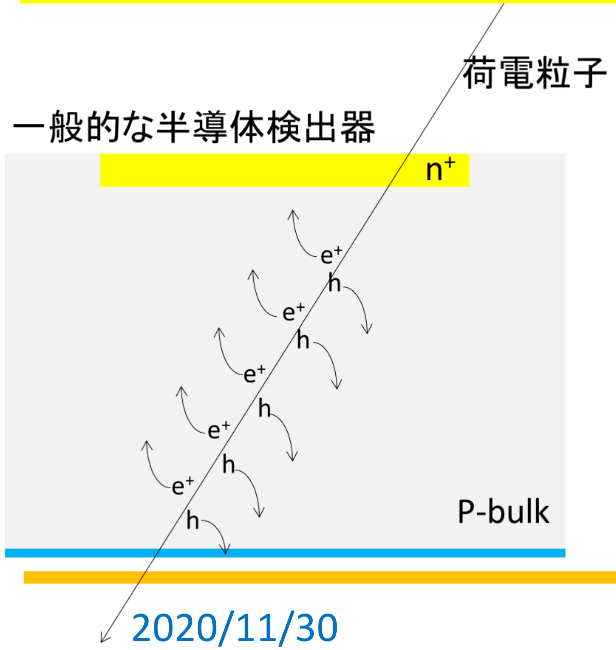
中村浩二 (KEK)

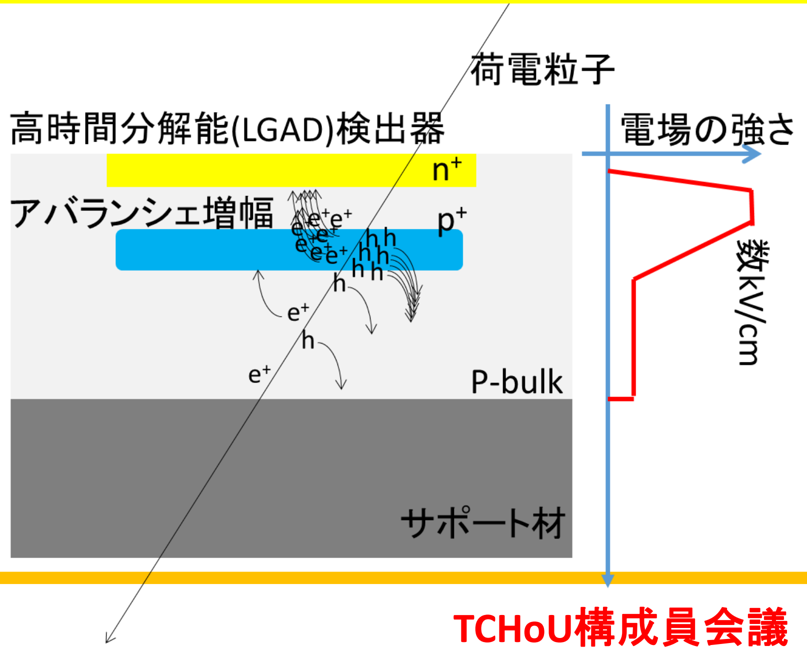
Introduction

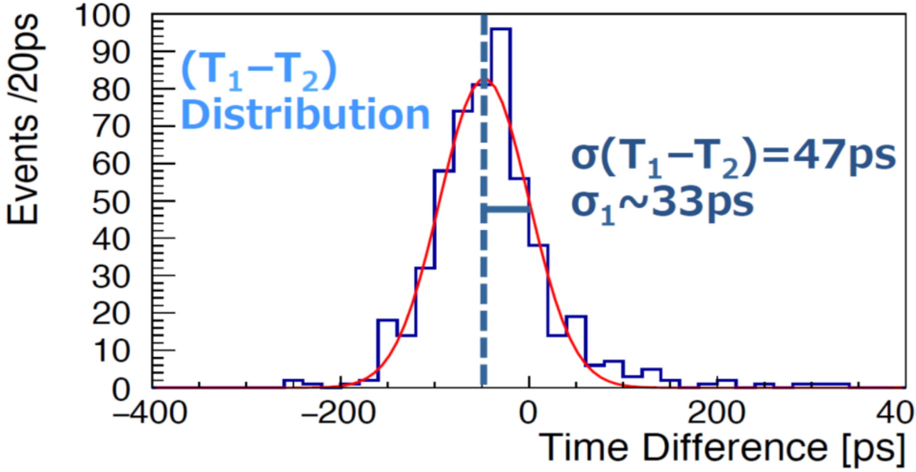


- 高輝度、高エネルギーハドロン衝突型加速器の最大の問題は**多重衝突**
  - 高輝度LHCで**140-200**衝突/事象、将来100TeV実験で**1400**衝突/事象
  - 飛跡検出器でこれを解決するには?
    1. ***ピクセルサイズの細密化***: →**読み出し速度の問題もあり1/10 (50→5um角)の改善は難しい…**
    2. ***時間分解能***: 飛跡を構成する検出器ヒットに時間情報があると革新的に改善→時間分解能 **30ps** で光速粒子の1cmを識別できる！

Low Gain Avalanche Diode (LGAD)の技術で30psの時間分解能を持つ半導体検出器が実現

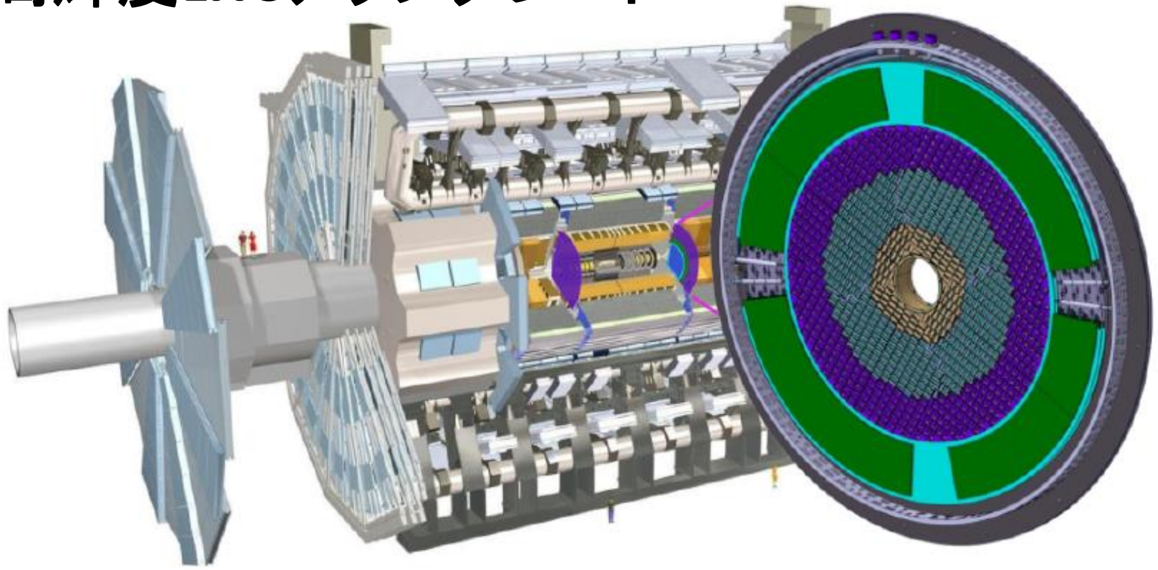






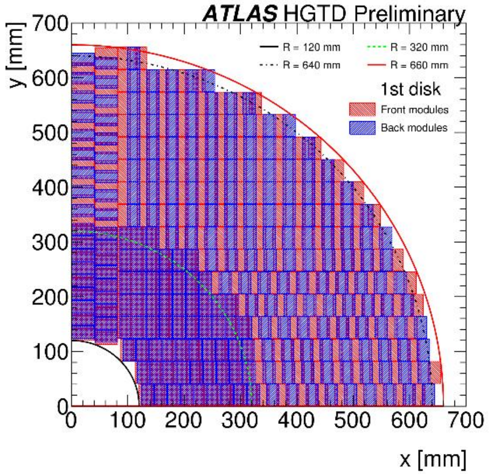
(参考)ATLAS 前方LGAD検出器(HGTD)

高輝度LHCアップグレード

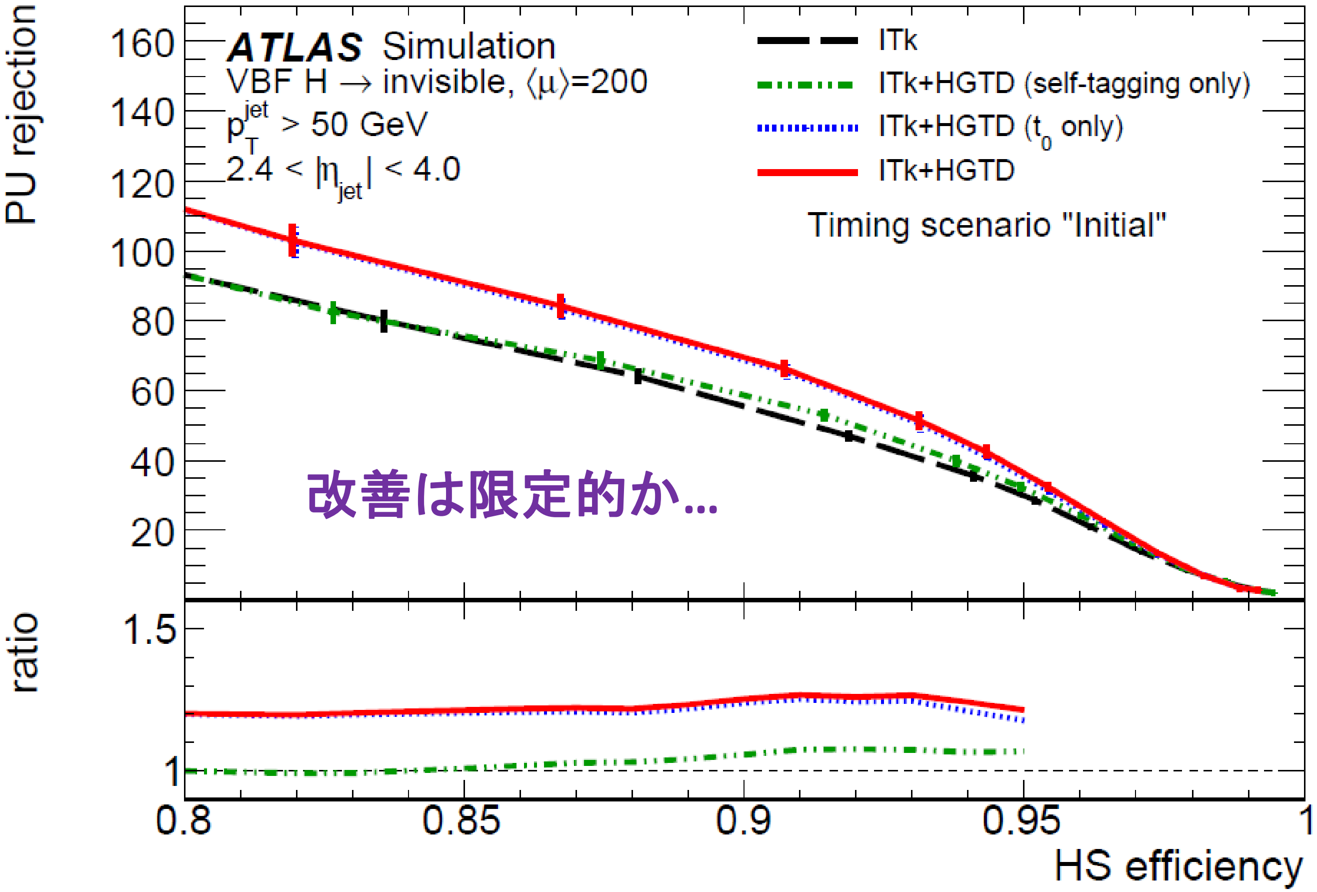


前方のカロリーメタ直前
4層のLGAD検出器
電極サイズは1.3mmx1.3mm

Tracking目的ではなく、
Trackに時間情報を追加する



Hard Scatter (HS)の衝突点を同定する効率とパイルアップ(PU)除去



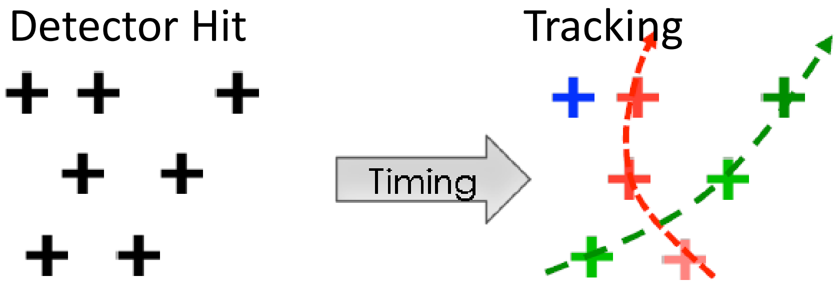
改善は限定的か…

次世代LGAD検出器への要求

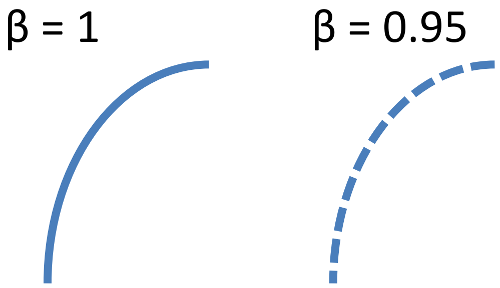
- 当然、時間分解能と位置分解能を兼ね備えた検出器が欲しい！

  →ゆくゆくは飛跡検出器全部をこの検出器で置き換える！
- ざっくり必要な性能
  - 30ps程度の時間分解能
  - ~o(10)um 位置分解能.
  - (ハドロン加速器用) ~o(10^{16})n_{eq}/cm^2 までの放射線耐性
- これが実現すると、

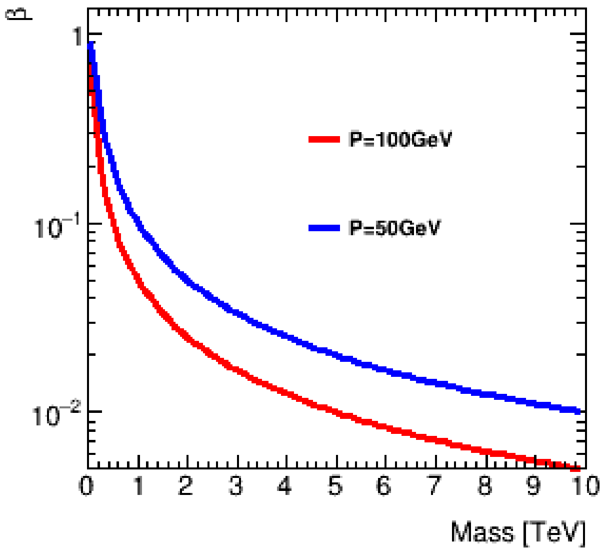
4次元トラッキング！



粒子識別や新粒子の質量測定



1mで150psの到達時間差



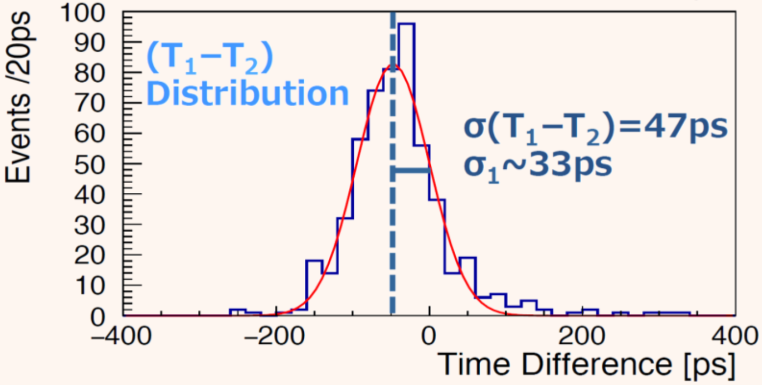
βを精度よく測ると質量が決まる

浜松ホトニクスでのLGAD検出器の歴史

First LGAD detector by HPK in 2015

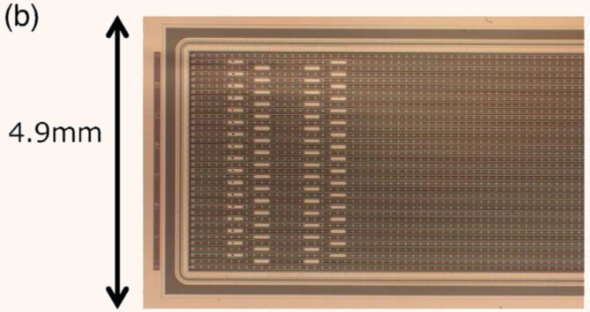
S.Wada et.al. NIMA Volume 924, Pages 380-386 doi:10.1016/j.nima.2018.09.143
K.Onaru et.al. NIMA Volume 985, 164664 doi:10.1016/j.nima.2020.164664

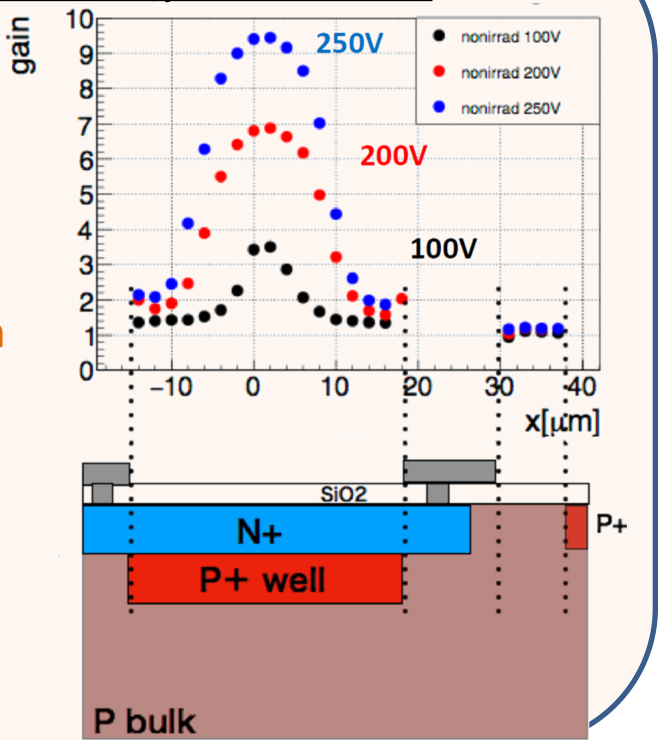
First PAD detector worked and evaluated 33ps timing resolution !!



First Strip detector had gain un-uniformity

80um pitch strip detector : only 20um region (25%) have gain





Second LGAD detector by HPK in 2018

R. Padilla et. al. 2020_JINST_15_P10003 doi:10.1088/1748-0221/15/10/P10003

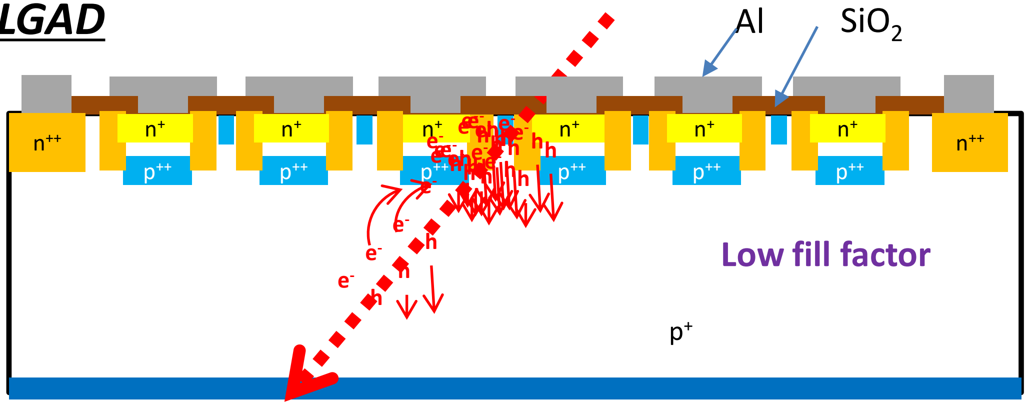
ATLAS/CMS run for HL-LHC timing detector

Optimization of process/doping profile/active thickness etc. by ATLAS/CMS collaboration

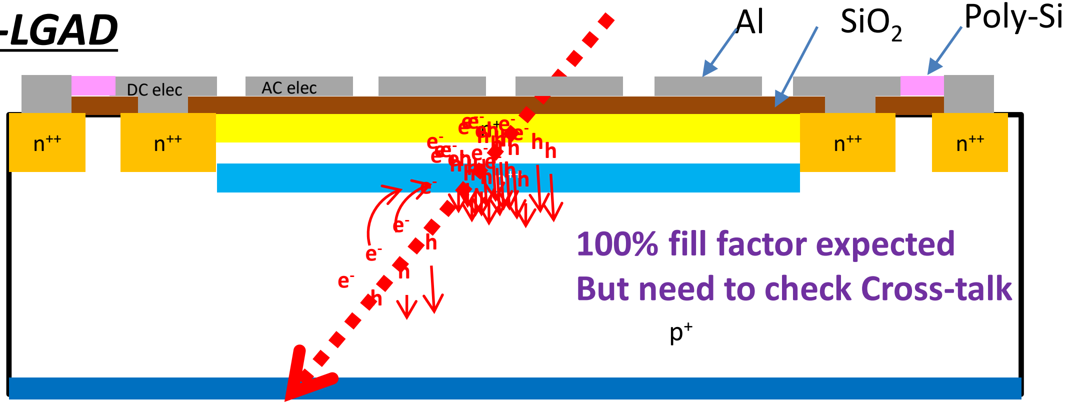
AC-LGAD検出器

- 以前作ったLGADストリップ検出器(80umピッチ)→有感領域が20%ほどしかなかった。
- 増幅層を共通にして、電極をAC的に配置→増幅率の非一様性がなくなる。
  - 信号がn+の中を走るのでクロストークがあるはず→ n+ドープ量を減らす。(= 抵抗値をあげる)

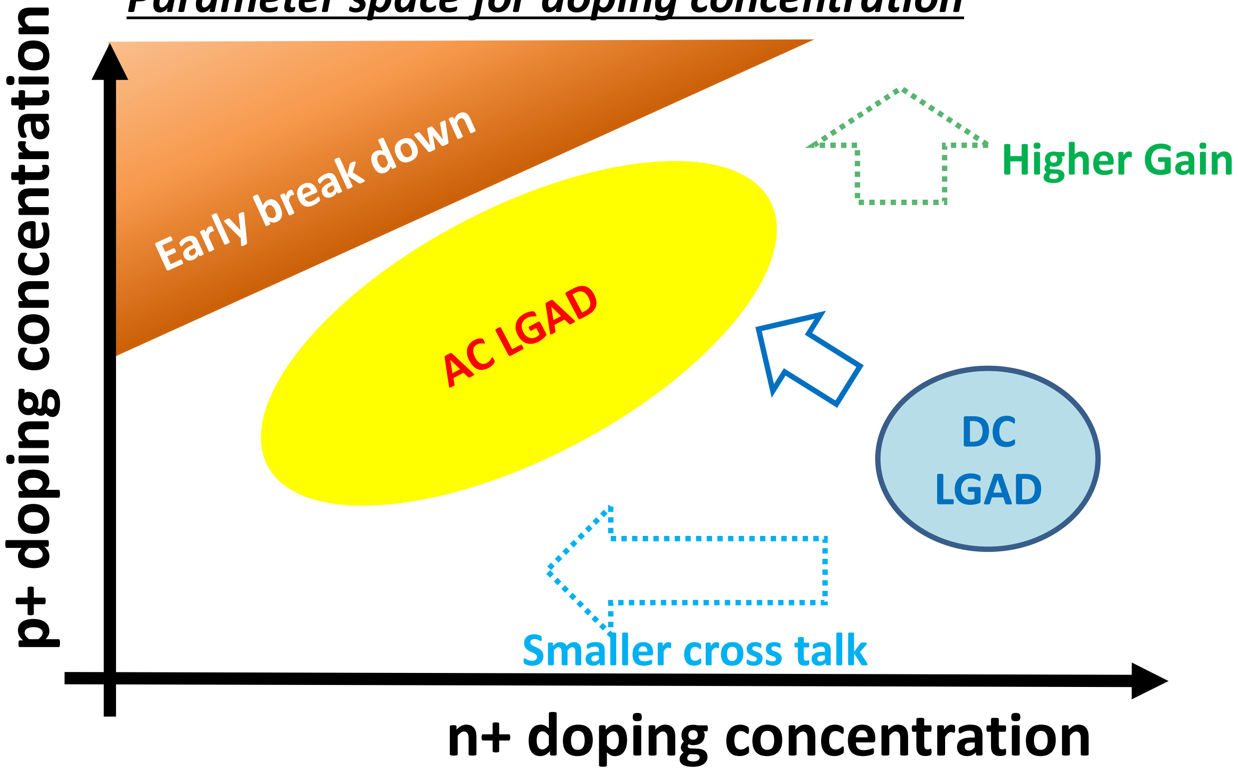
DC-LGAD



AC-LGAD



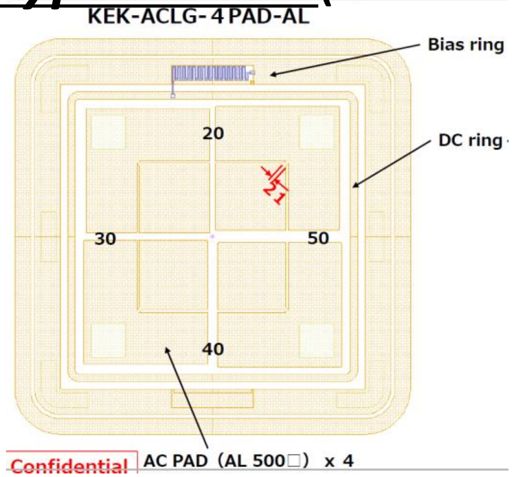
Parameter space for doping concentration



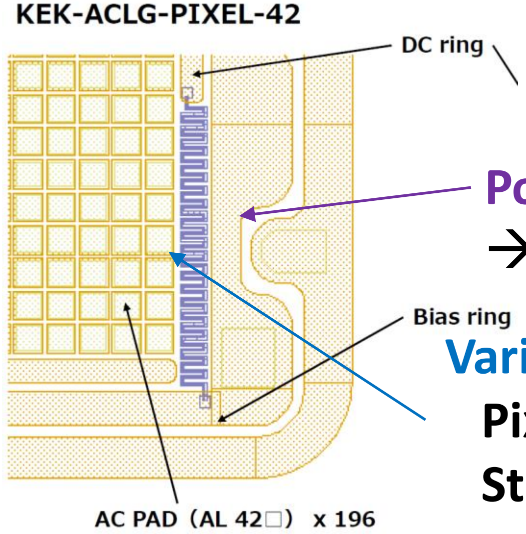
最初の AC-LGADプロトタイプ (浜ホト製)

50um Active thickness

Pad type sensor (4x 450umx450um)



Pixel type sensor (14x14 50umx50um)



Poly-si resistor between DC ring and Bias ring(GND)

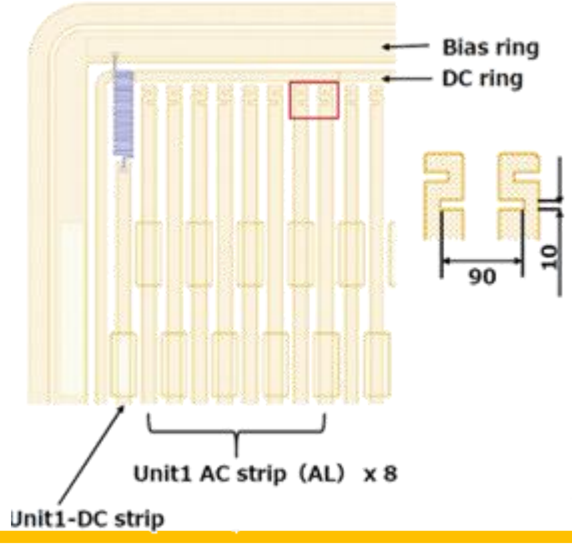
→ To free up charge in n+.

Varied Al size (AC coupling capacitance size)

Pixel : 42/38/34/30 um width/length

Strip : 47/42/37/32 um width

Strip type sensor (16x 80um pitch)



Varied n+ and p+ doping concentration

p+ doping

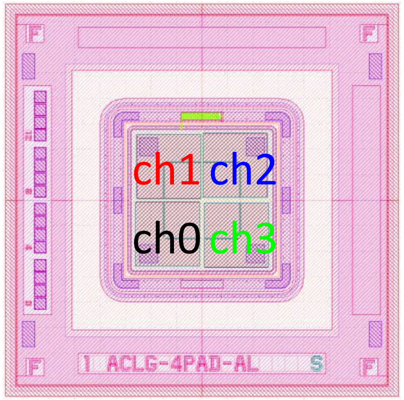
		N+ doping concentration / resistivity		
		C(Ax10 resistivity)	B(Ax3.3 resistivity)	A (~DC-LGAD)
P+ doping concentration	3 (high)	■	B-3	A-3
	2 (mid)	C-2	B-2	A-2
	1 (low)	C-1	B-1	■

n+ doping

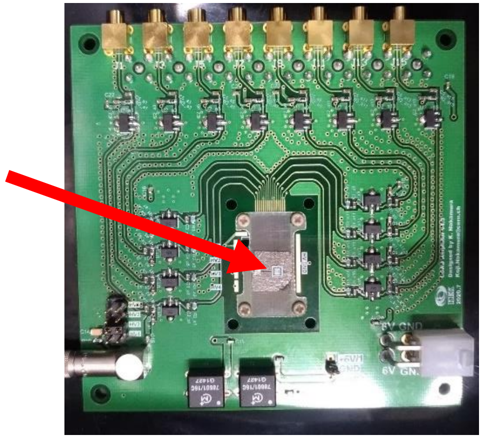
Pulse shape measurement

- To detect signal from AC-LGAD
  - Used ^{90}Sr β source
  - Discrete Amp has been designed by Fermilab and modified/produced at KEK.
  - Pulse detected by CAEN DT5742 digitizer
  - Triggered by Scintillator with MPPC readout

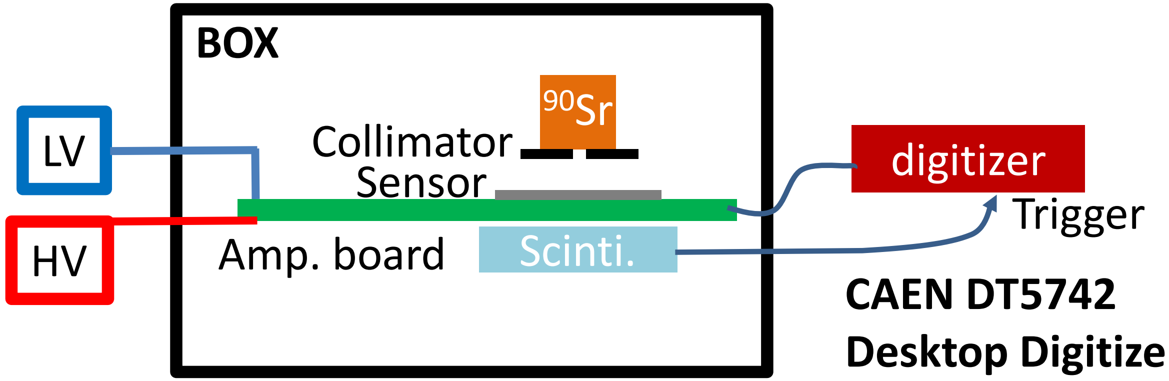
Pad Sensor



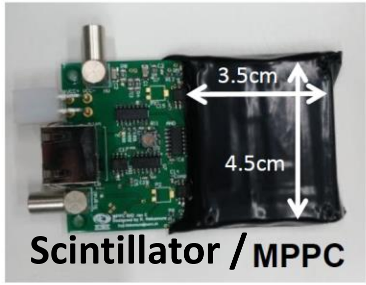
KEK
16 ch Discrete Amp.



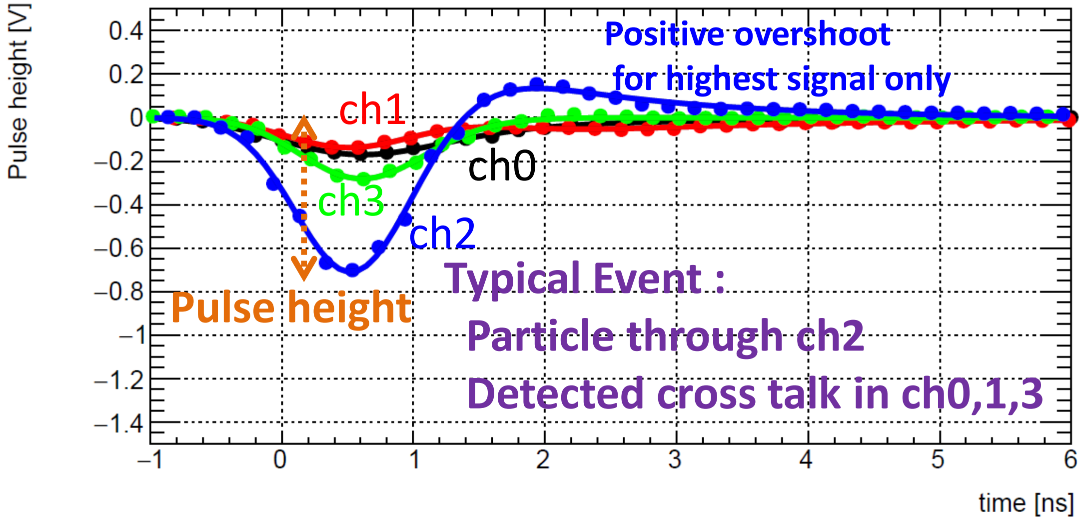
Fermilab
16 ch Discrete Amp.



CAEN DT5742
Desktop Digitizer
5GS/s 10bit
12bit ADC 2V full range



Scintillator / MPPC

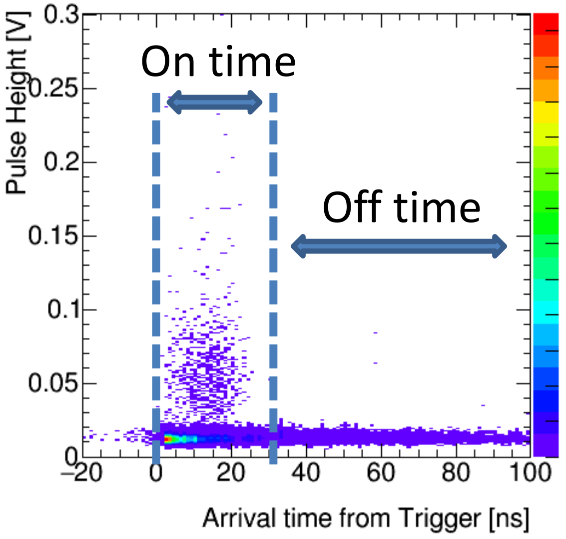


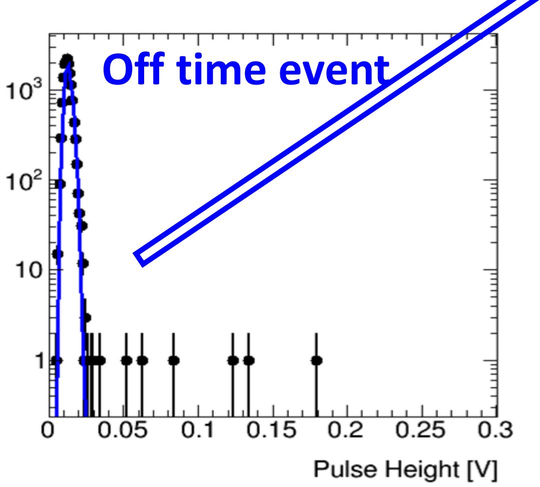
Positive overshoot for highest signal only

Typical Event :
Particle through ch2
Detected cross talk in ch0,1,3

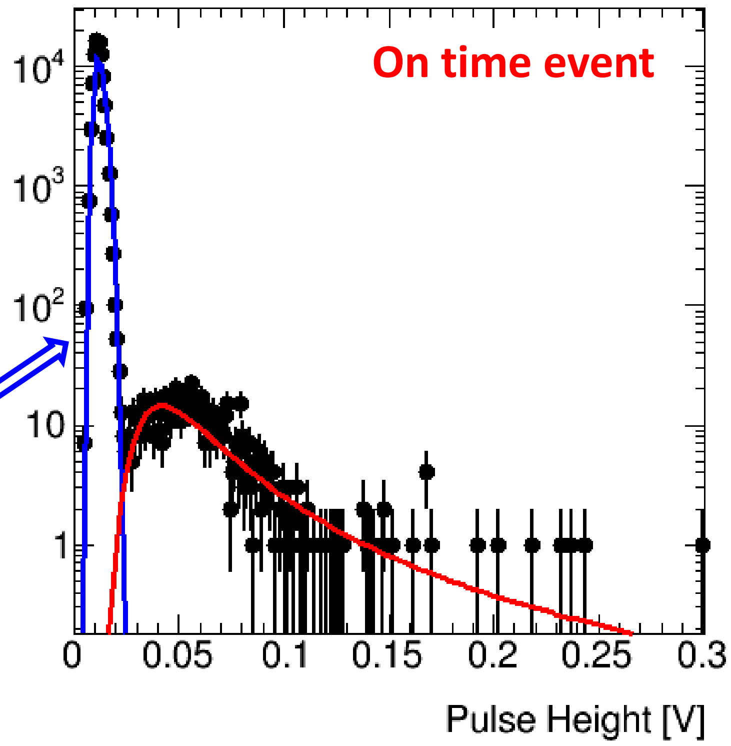
Pulse Height and Bias Voltage dependence

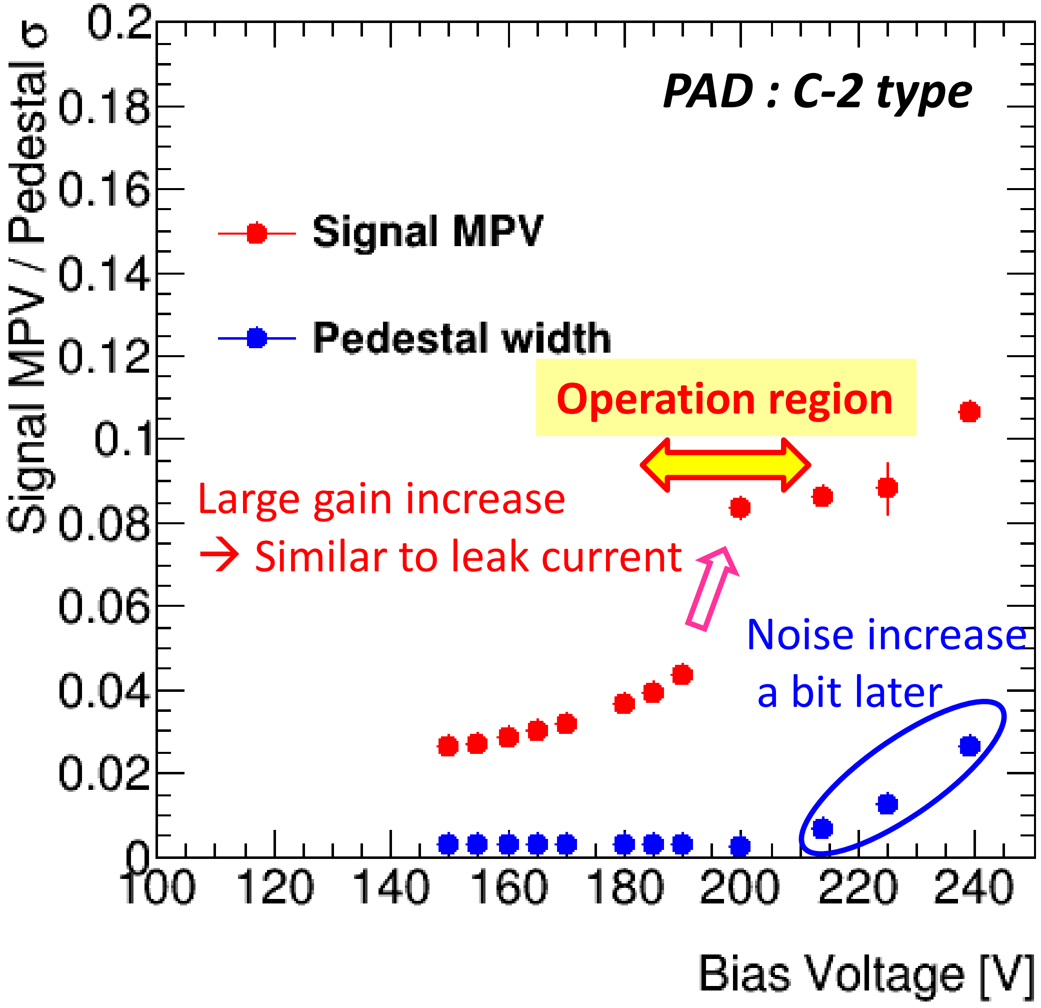
Pedestal distribution is evaluated from off timing region





Example : 190V Bias Voltage





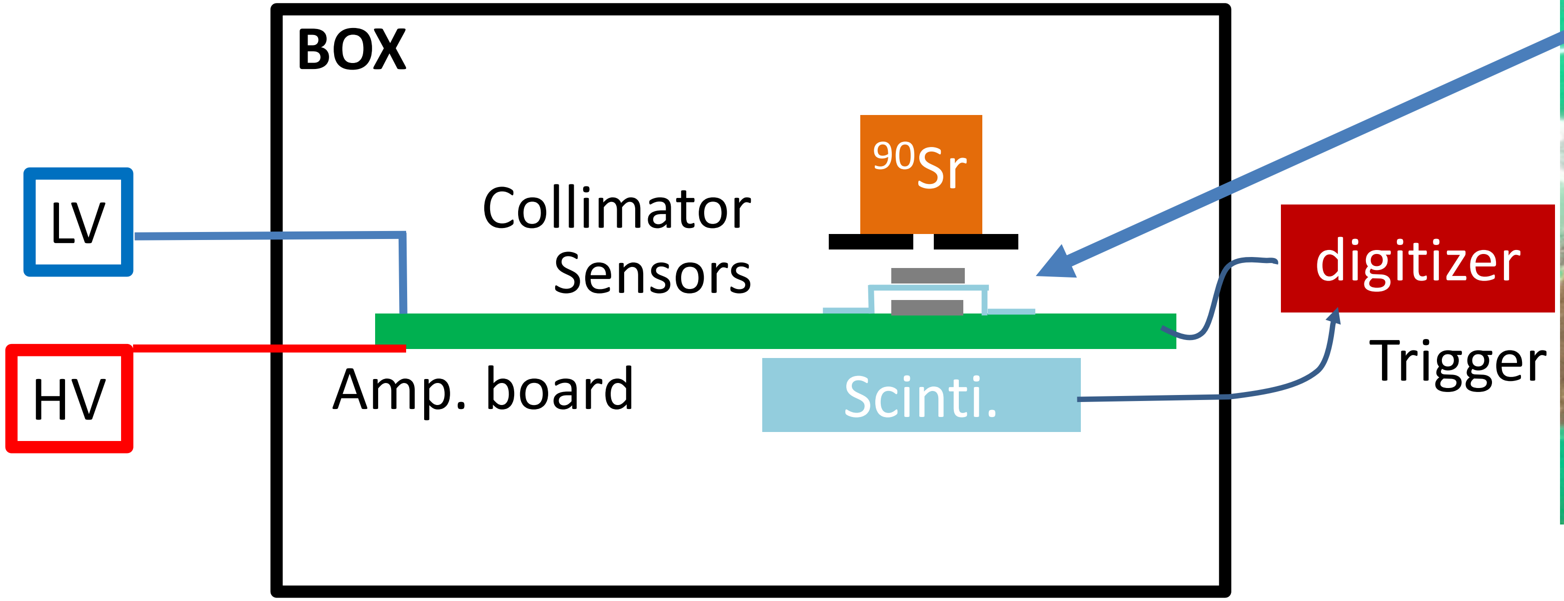
Operation region

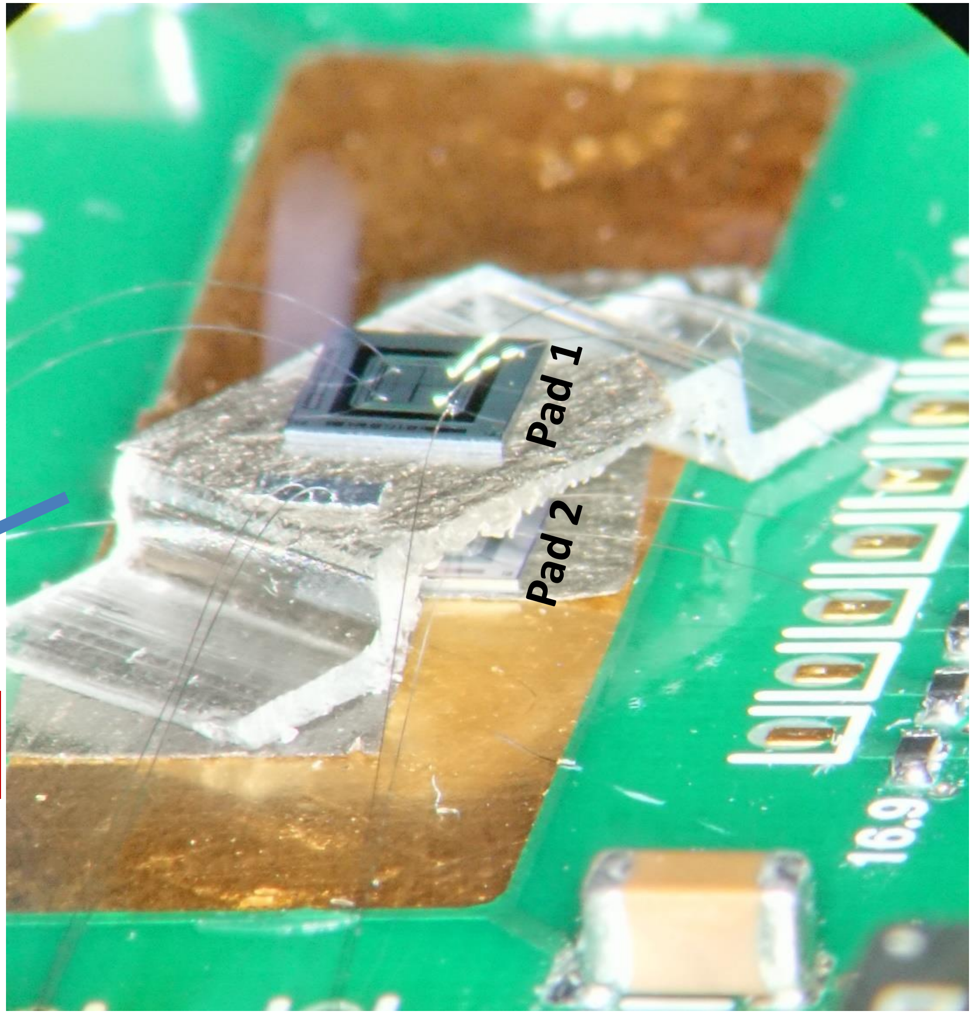
Large gain increase
→ Similar to leak current

Noise increase
a bit later

Time resolution

- To evaluate timing resolution, two same type of pad sensors are stacked interleaved by using plastic piece.
  - Sigma of time difference : $\sigma(T_1\text{-}T_2)=\sqrt{(\sigma_1)^2+(\sigma_2)^2}$
  - In case two same type sensors : $\boldsymbol{\sigma_t = \sigma(T_1\text{-}T_2)/\sqrt{2}}$

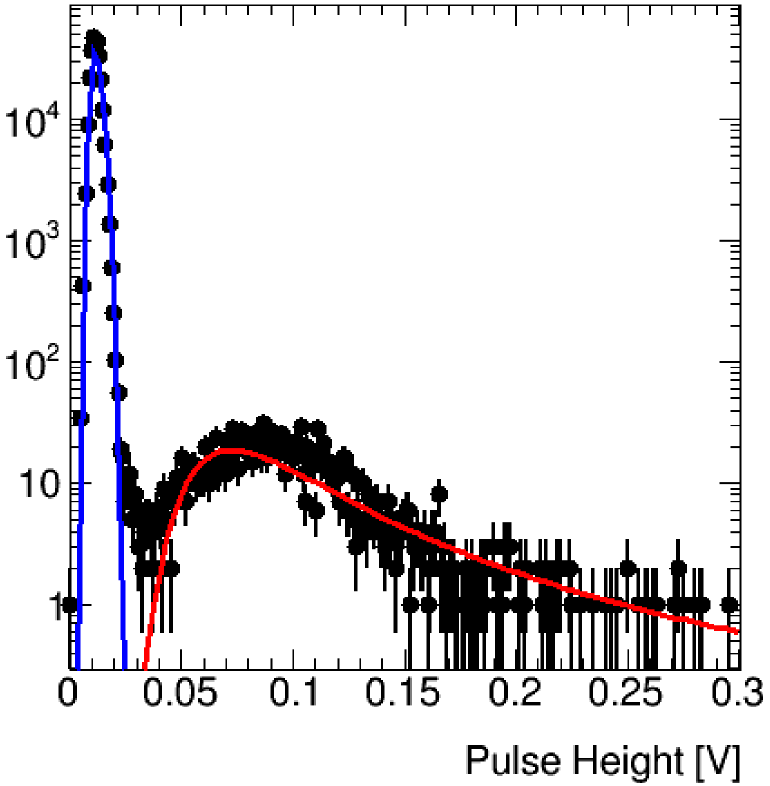




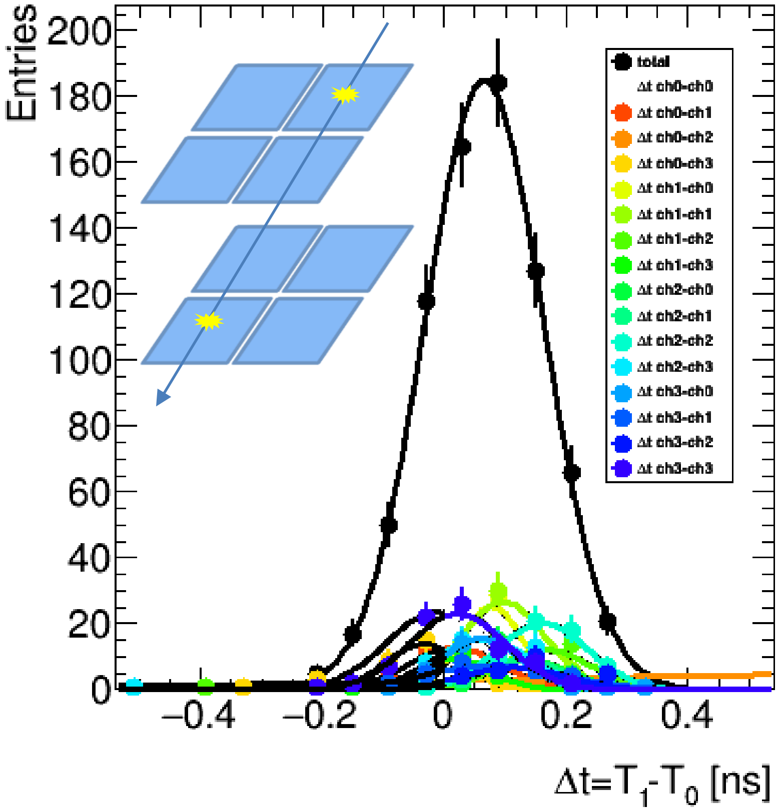
Time resolution

- Time difference has been calculated separately for all combination of channels in top and bottom channel then combined.
- **Evaluated ~45ps time resolution at 200V.**

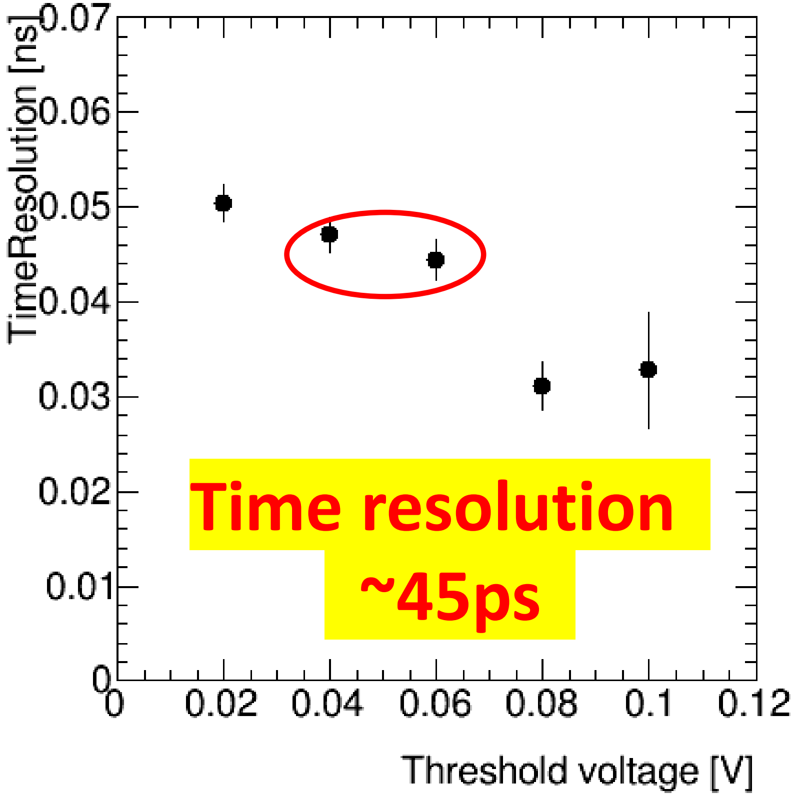
Pulse Height Distribution



Time difference of pad 1 and 2



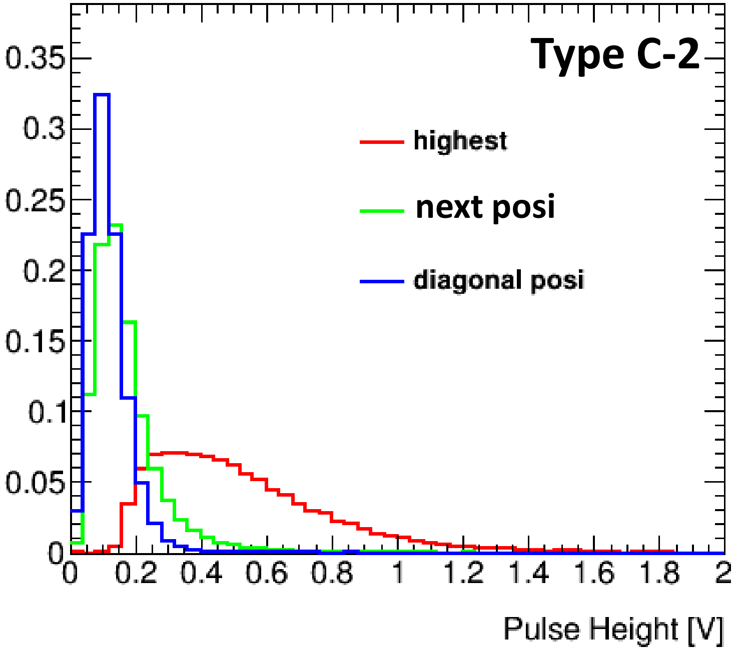
Timing resolution with certain threshold

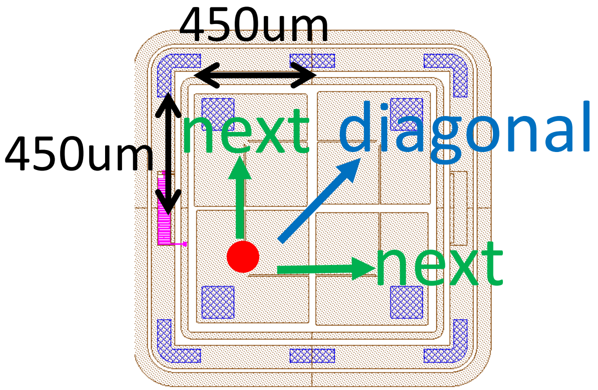


Time resolution ~45ps

Crosstalk

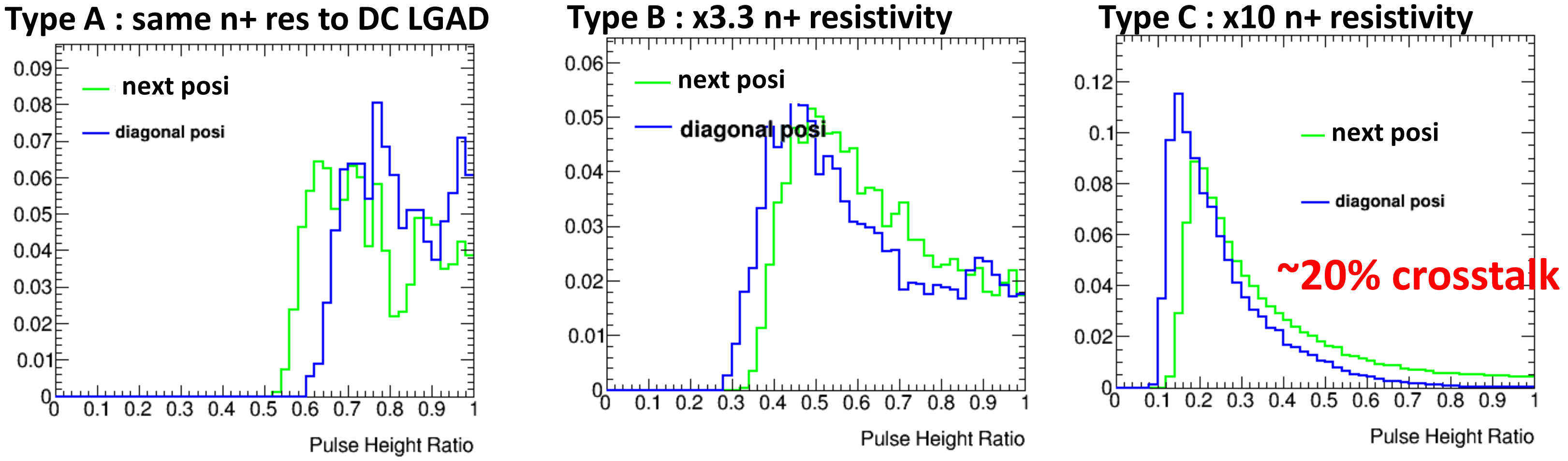
Pulse height





- ***Pulse height distribution***
  - type C-2 (x10 n+ resistivity) show good separation of signal and crosstalk.
- ***Cross talk depends on n+ resistivity***
  - Higher resistivity have smaller crosstalk
  - **~20% crosstalk for type C (x10 n+ resistivity)**

Pulse height ratio to the Leading pulse height

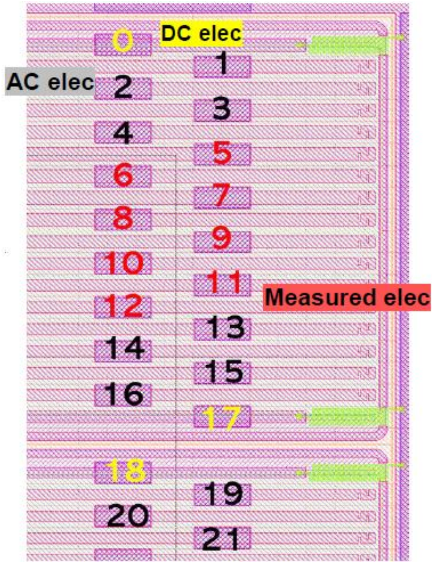


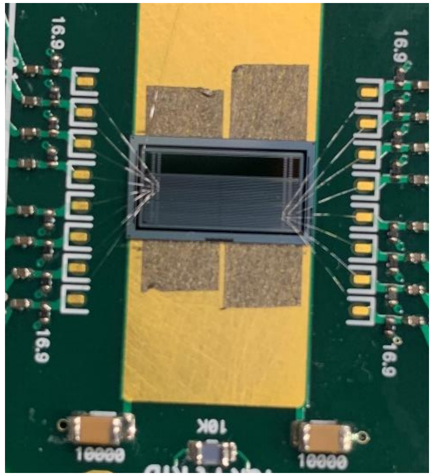
Distance dependence of Crosstalk

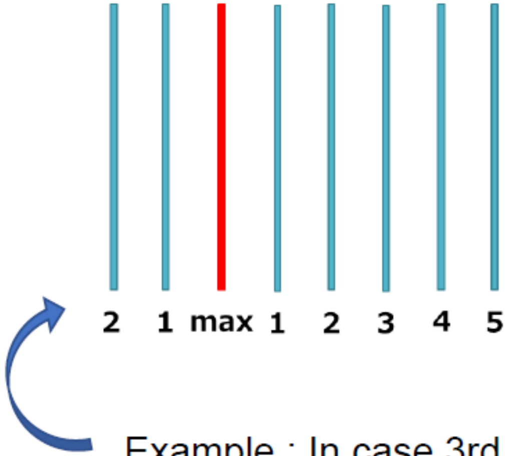
困ったこと①

- Crosstalk should depend on distance of electrode.
  - To check the dependence, **strip sensor** (80um pitch) is used
  - Pulse height ratio to leading strip is plotted as a function of distance (unit of strips)
  - **~75% @ 80um, ~62% @ 160um distance.**
  - **The strip where particle passed can be identified, but better to have smaller crosstalk.** → will test higher n+ resistivity

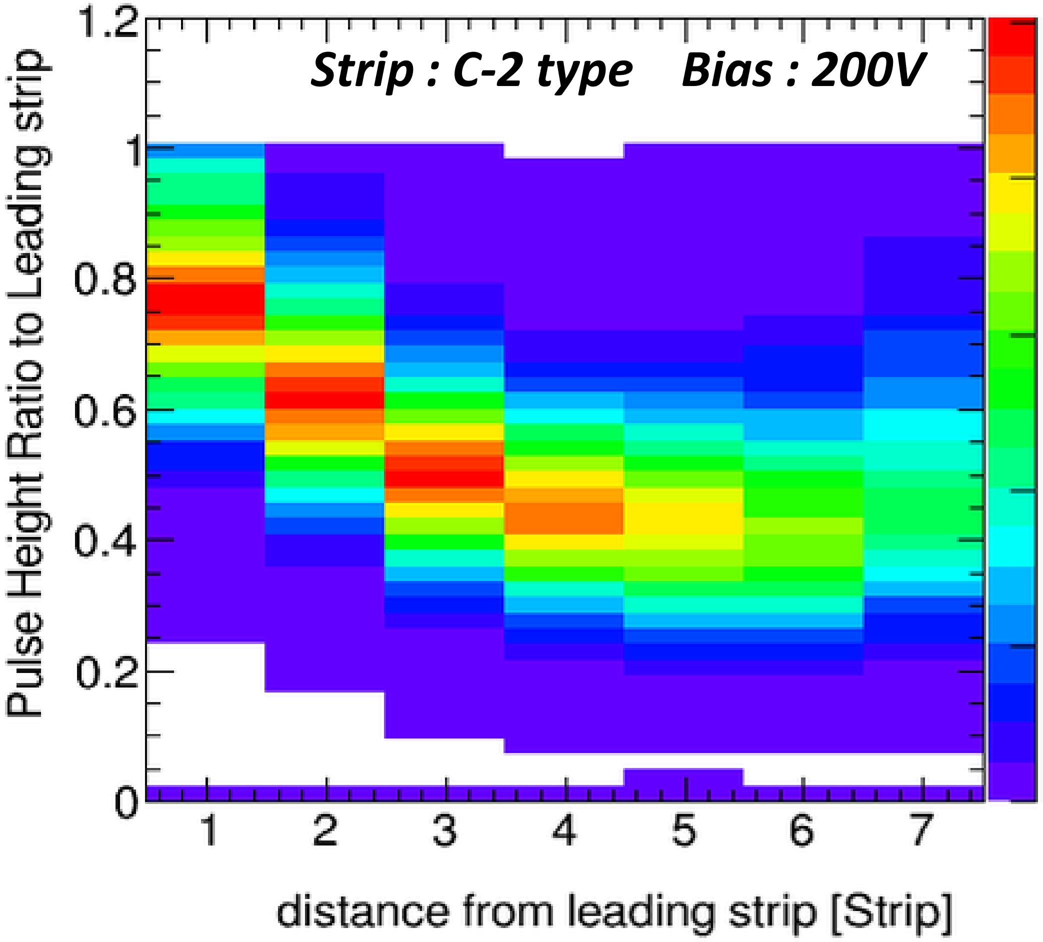
Strip Sensor







Example : In case 3rd left strip has highest pulse height



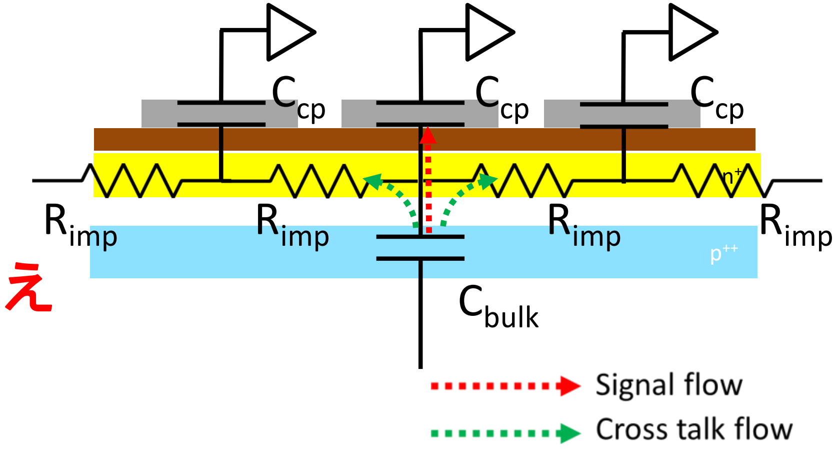
距離の影響もあるが…
パッドに比べてクロストークが大

Coupling capacitance and signal size

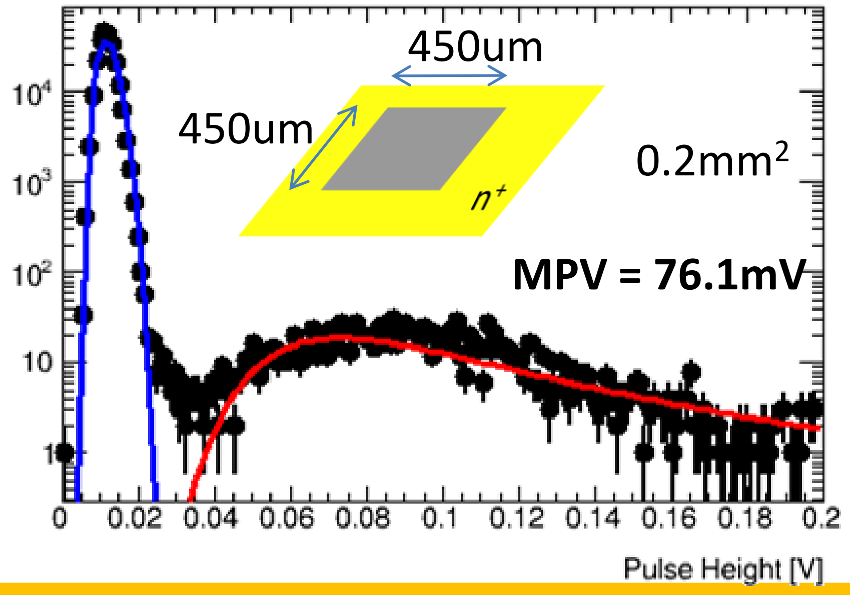
困ったこと②

- PADとStripセンサーの波高分布の比較(ともにC-2タイプ200V)
  - n+ と p+ のドープ量は同じ→同じ C_{bulk}.
  - 増幅された信号は、電極方向(C_{cp})とn+抵抗方向(R_{imp})に分離
    - インピーダンスの小さい方に流れやすい。
    - パッドとストリップで大きな差があるのは $1/\omega C_{cp} >> R_{imp}$ か？
  - R_{imp} を大きくすることで信号の波高も大きくなりクロストークが抑えられるのではないか？→ DCLGADの100倍程度の抵抗が欲しい

Equivalent Circuit



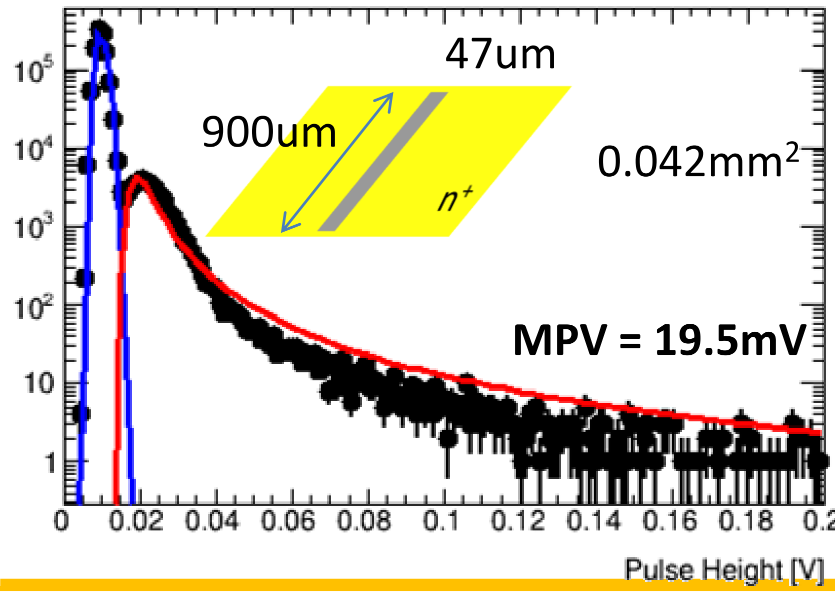
Pad Sensor



Area
x4.5

Signal
x3.9

Strip Sensor



考えられる仮説

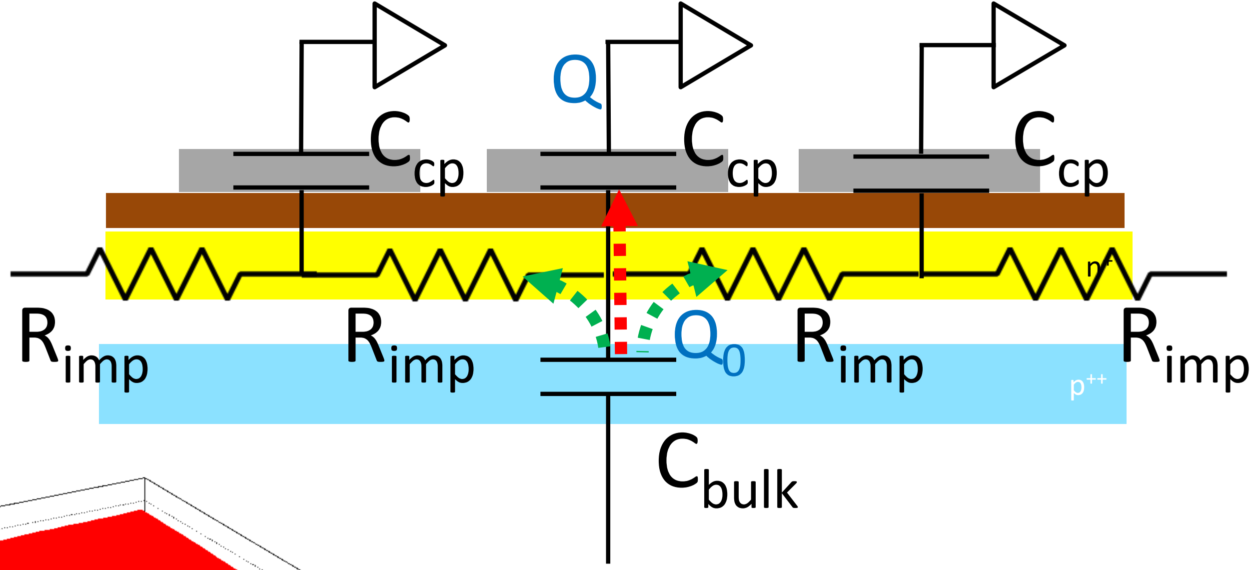
- 電荷の分離：インピーダンス比

$Z_{cbulk} >> Z_{Ccp}$と仮定して…

$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0$$

  - アバランシェでできた電荷Q_0
  - 電極から読み出される電荷Q

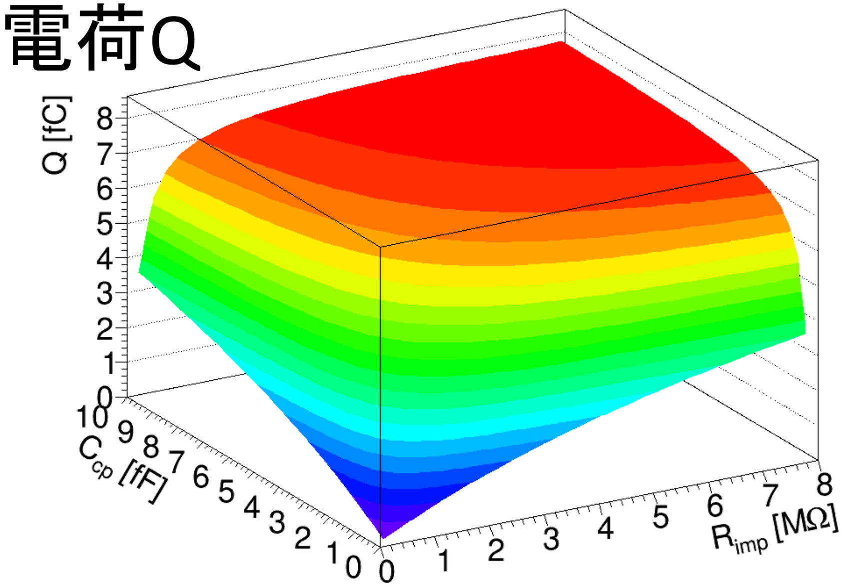
Equivalent Circuit



信号が大きくなる条件

Ccpが大きい

Rimpが大きい



この仮説を
TCADシミュレーションで確認
実データと比較

TCAD simulation

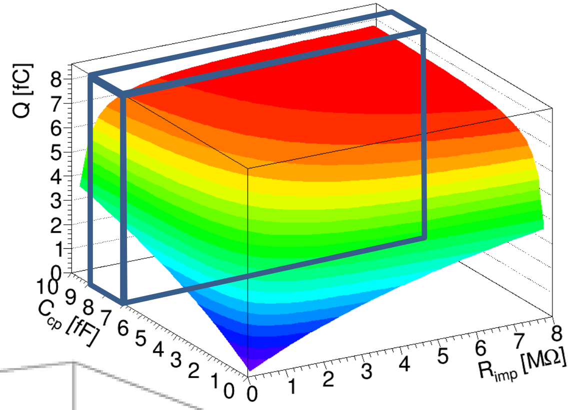
- TCAD(電場シミュレータ)で2Dモデルを作成

<u>Fixed parameters</u>

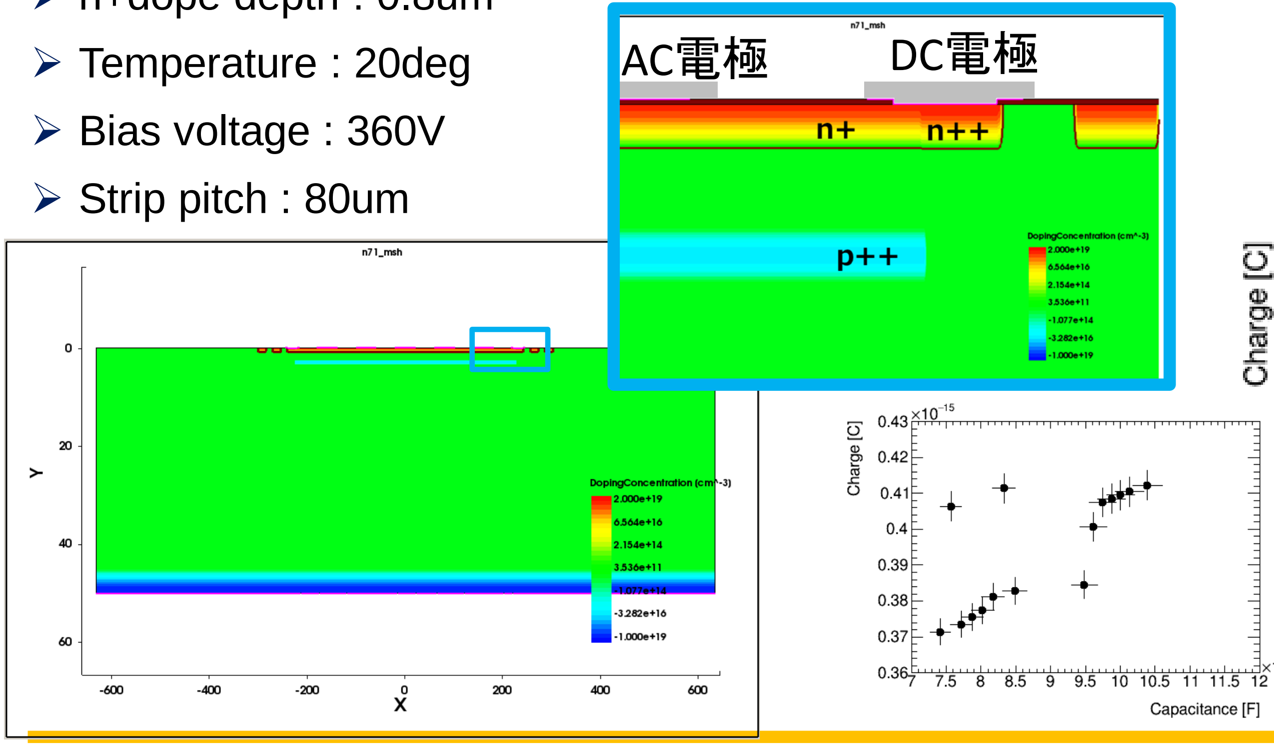
- ➢ Electrode : DC×2, AC×5
- ➢ Sensor thickness : 50um
- ➢ Oxide thickness : 0.1um
- ➢ n+dope depth : 0.8um
- ➢ Temperature : 20deg
- ➢ Bias voltage : 360V
- ➢ Strip pitch : 80um

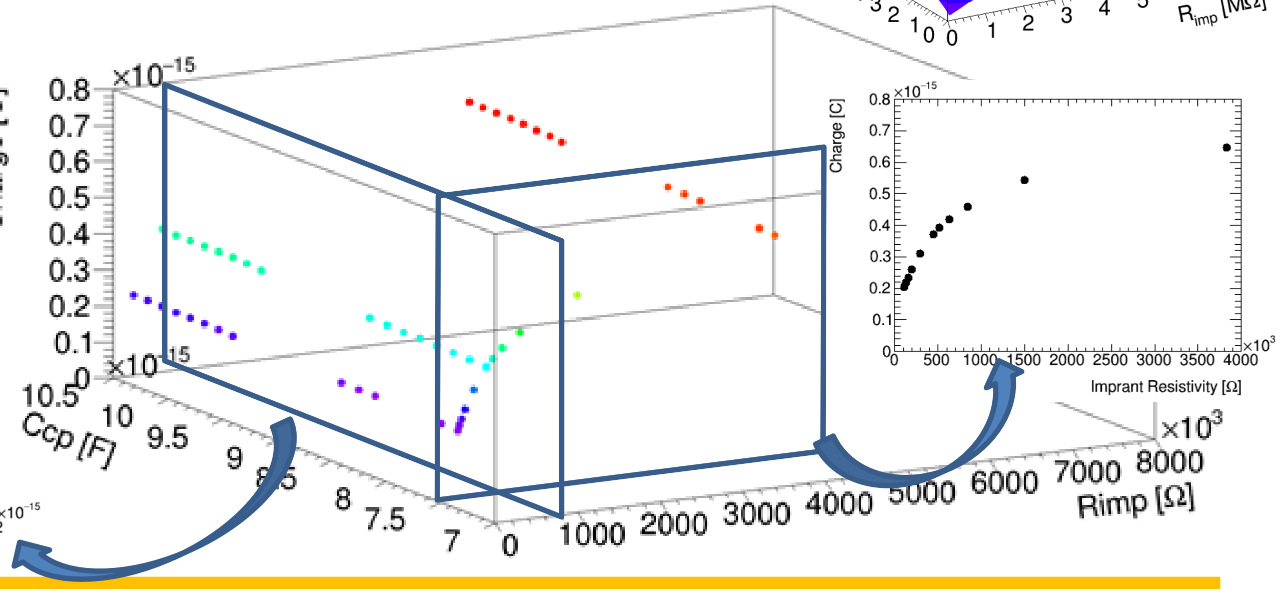
Rimp : n+のドープ量を 1e17 – 1e19 [atm/cm^3]で変化
Ccp : Al 電極サイズを 32um – 47umまで変化

Ccpは狭い領域のみ…



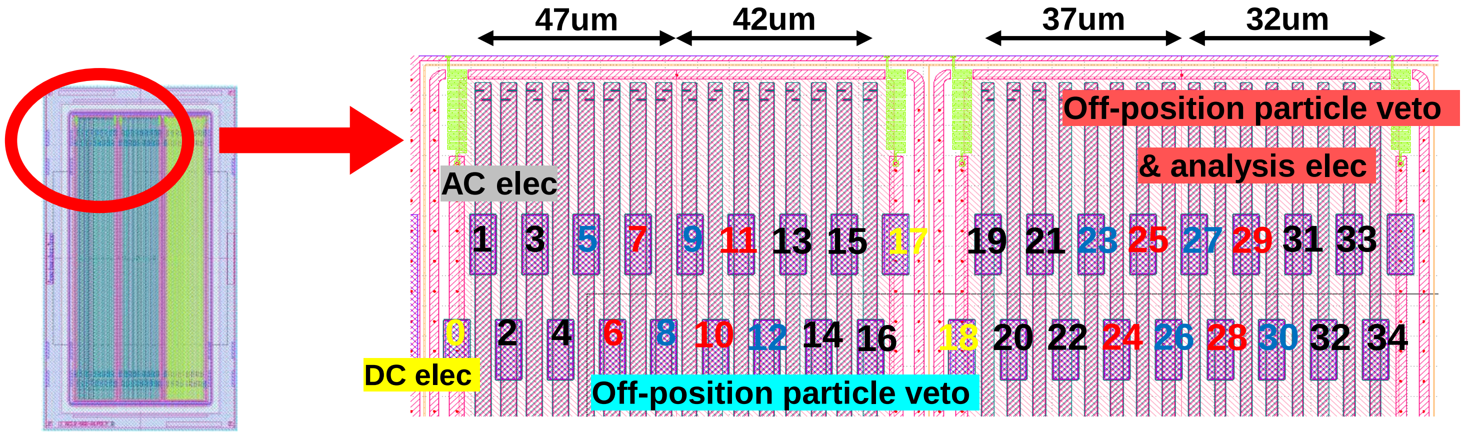
<u>シミュレーション結果</u>



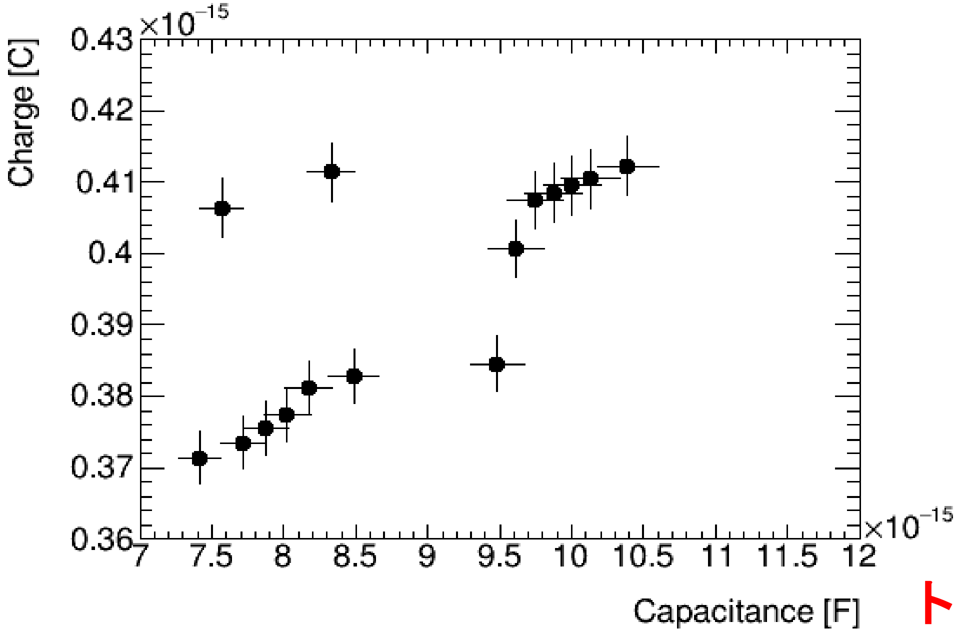


TCAD vs 実測

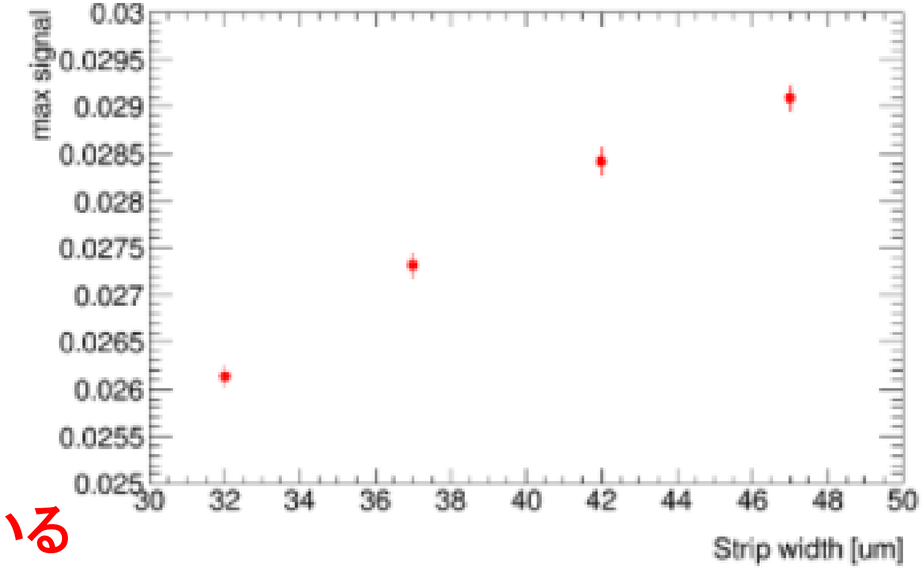
- Alサイズの異なるストリップを違って収集電荷のCcp依存性をシミュレーションと実測で比較



TCADシミュレーション結果



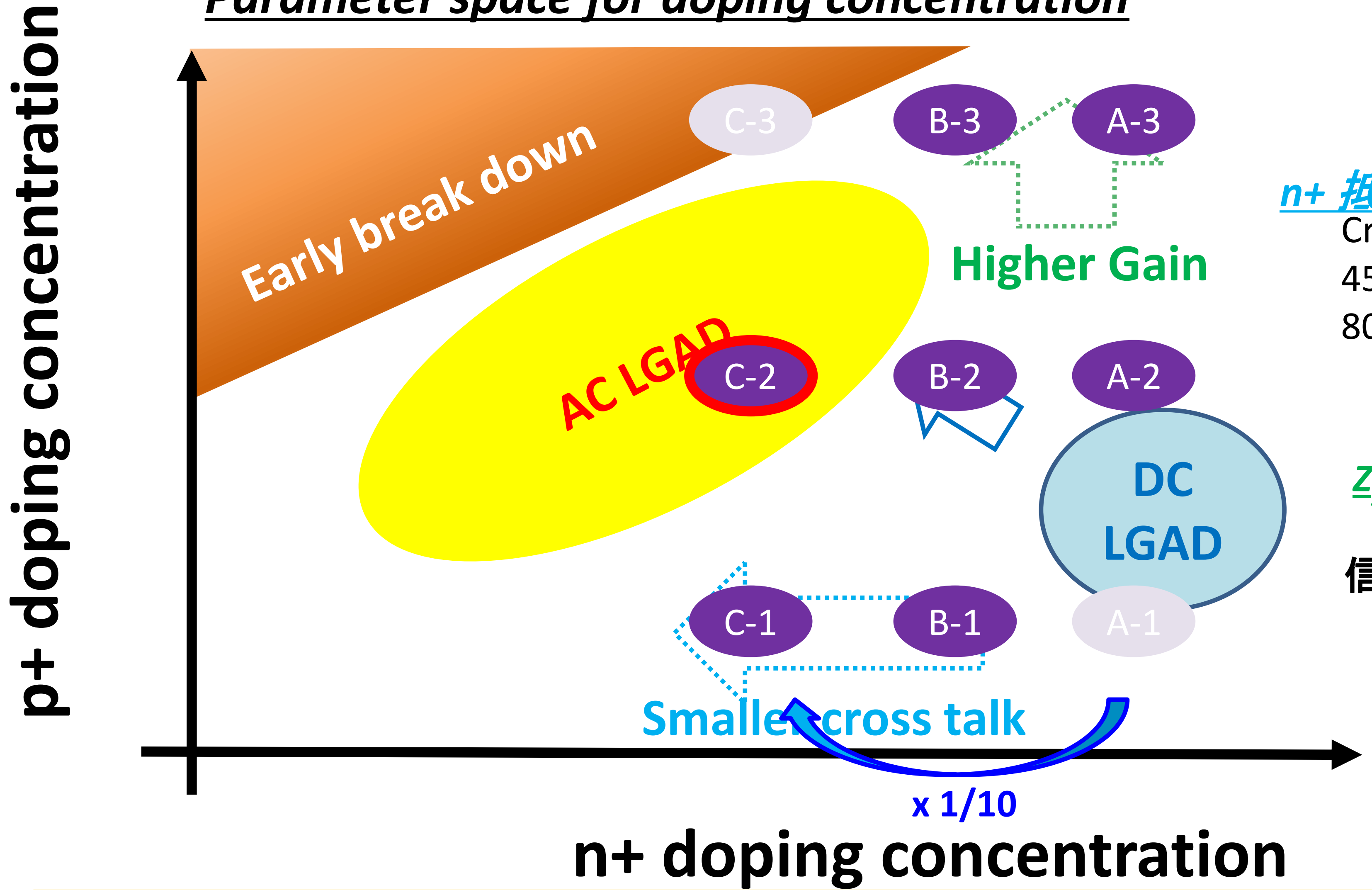
実測定結果



トレンドは再現している
絶対値は3Dシミュレーションが必要か…

Conclusion & Plan

Parameter space for doping concentration



● **fabricated at HPK**

電極の細密化をしたAC-LGADも
LGAD検出器として動いている！

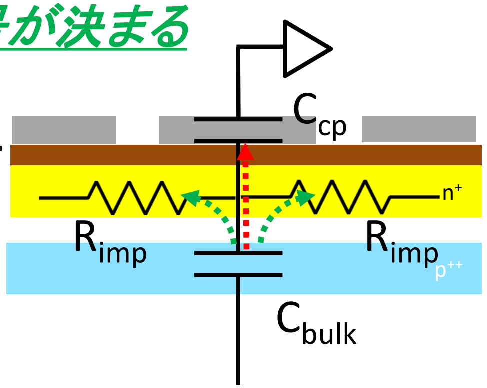
n+ 抵抗が高いほどクロストークが抑制できる

Cross talk : x10 n+ resistivity sample (C-2 type)
450um角のパッド検出器 : **20%**
80um pitch strip : **75%** @隣のストリップ

時間分解能は~45ps→要検査

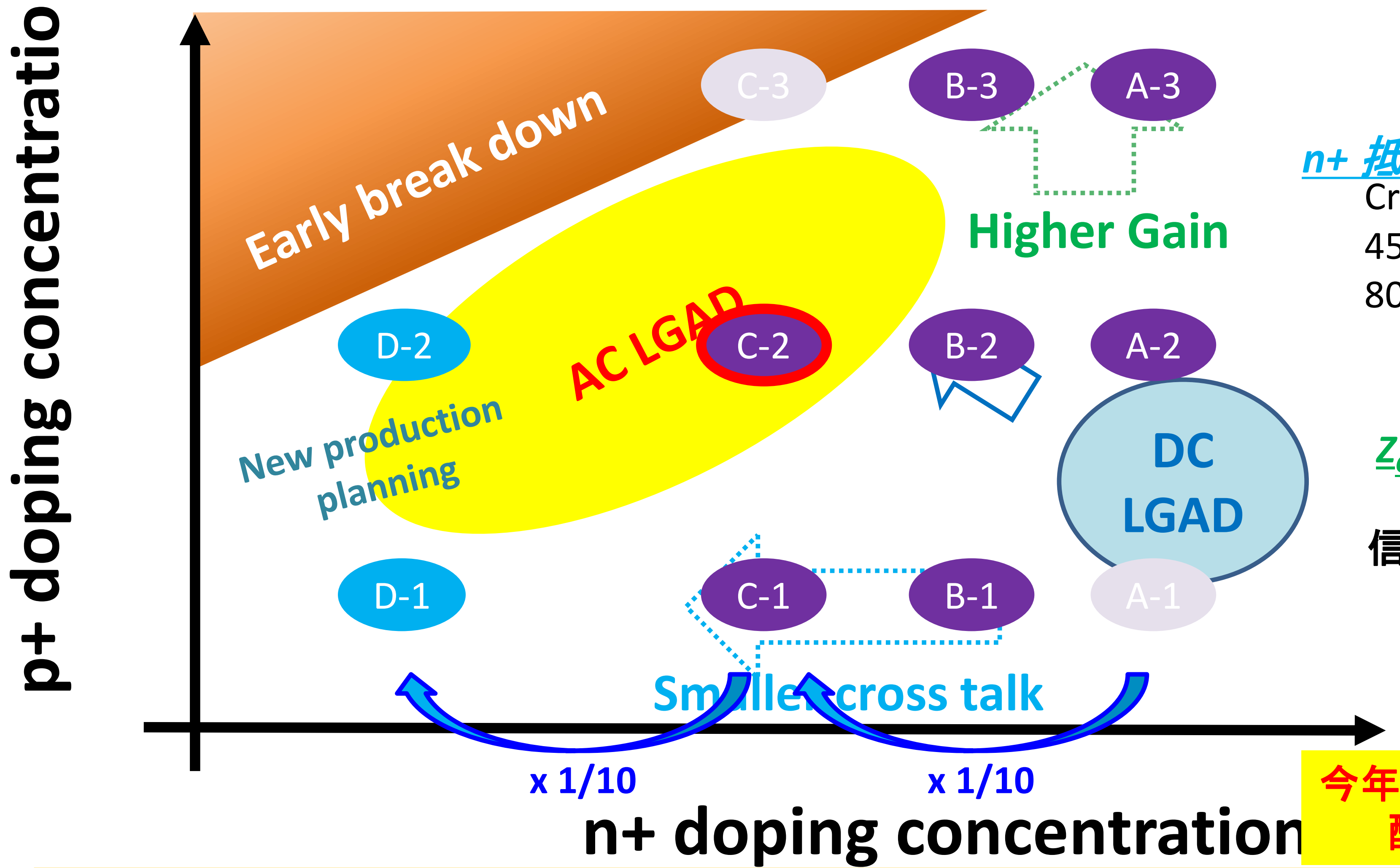
Z_{Ccp}とZ_{Rimp}の比で信号が決まる

信号が大きくなる条件
Ccpが大きい
Rimpが大きい



Conclusion & Plan

Parameter space for doping concentration



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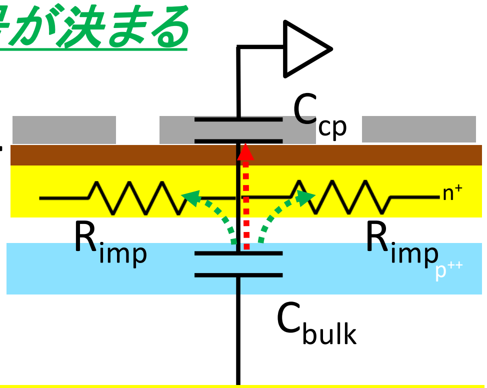


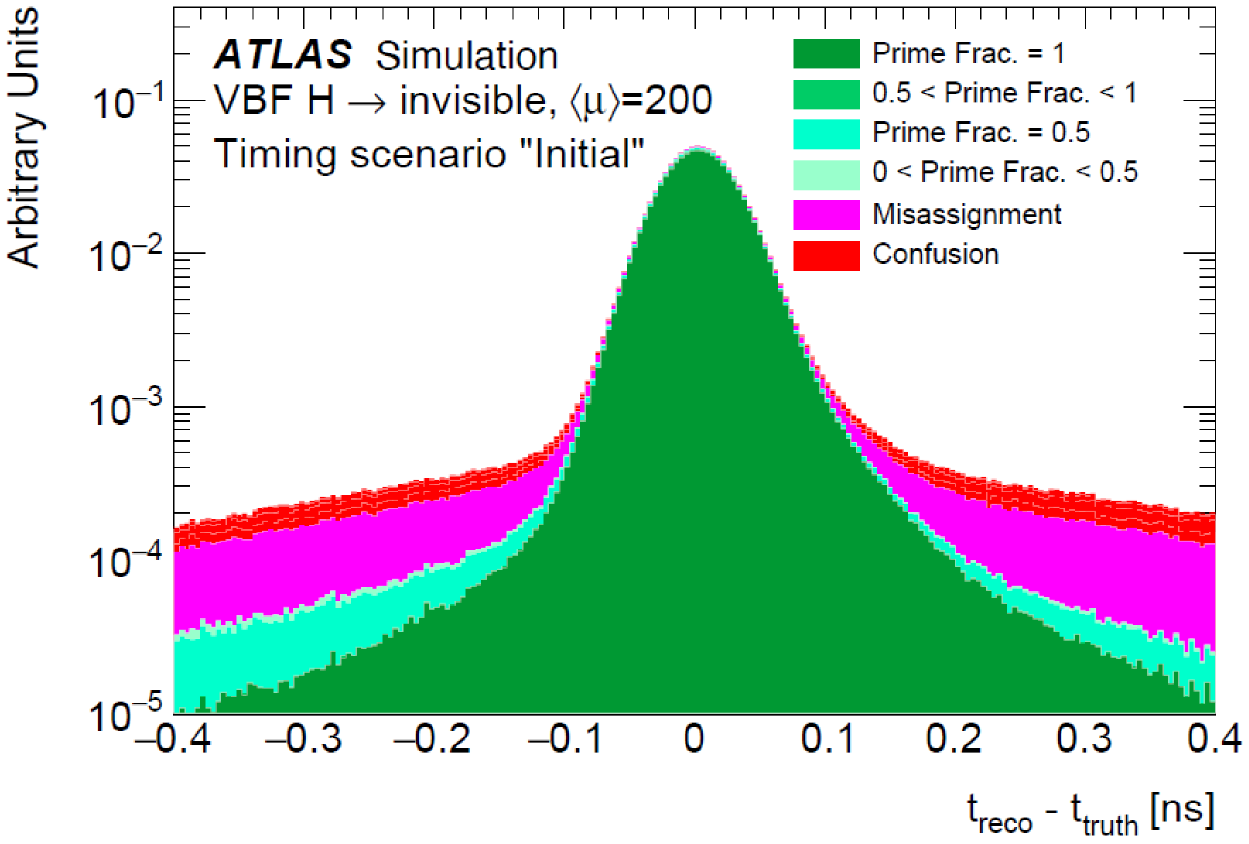
信号が大きくなる条件
Ccpが大きい
Rimpが大きい

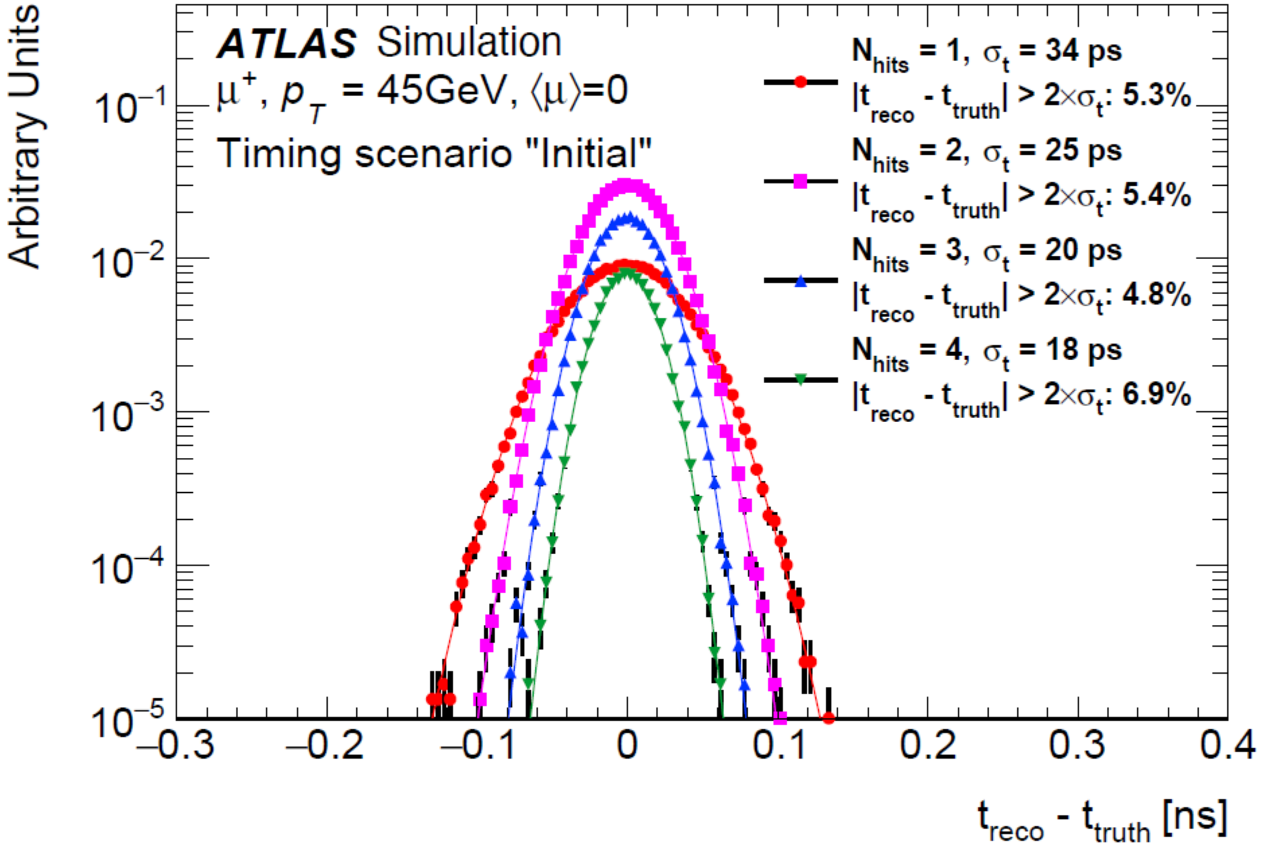
Plan

今年度の予算でn+濃度を1/10にしたサンプルと
酸化膜圧を1/2にしたサンプルを製造中

backup

ATLAS 前方LGAD検出器(HGTD)





IV-カーブ

Varied n+ and p+ doping concentration

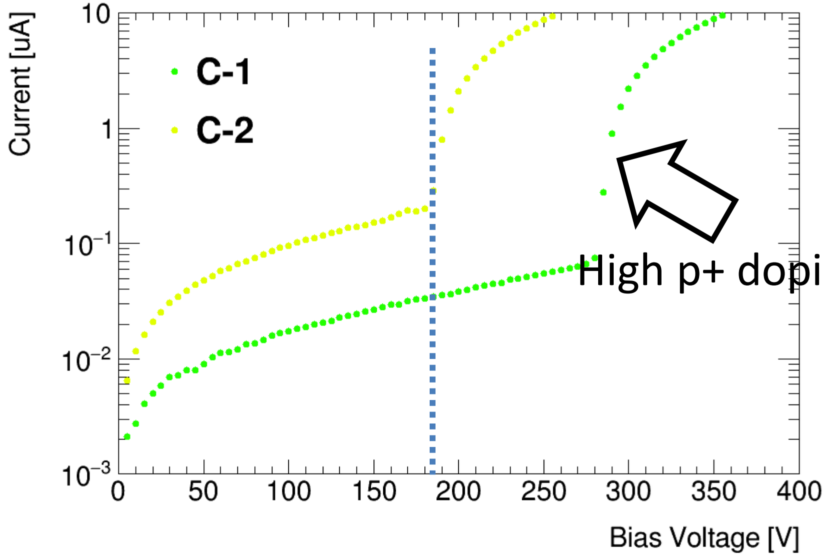
		N+ doping concentration / resistivity		
		C(Ax10 resistivity)	B(Ax3.3 resistivity)	A (~DC-LGAD)
P+ doping concentration	3 (high)		B-3	A-3
	2 (mid)	C-2	B-2	A-2
	1 (low)	C-1	B-1	

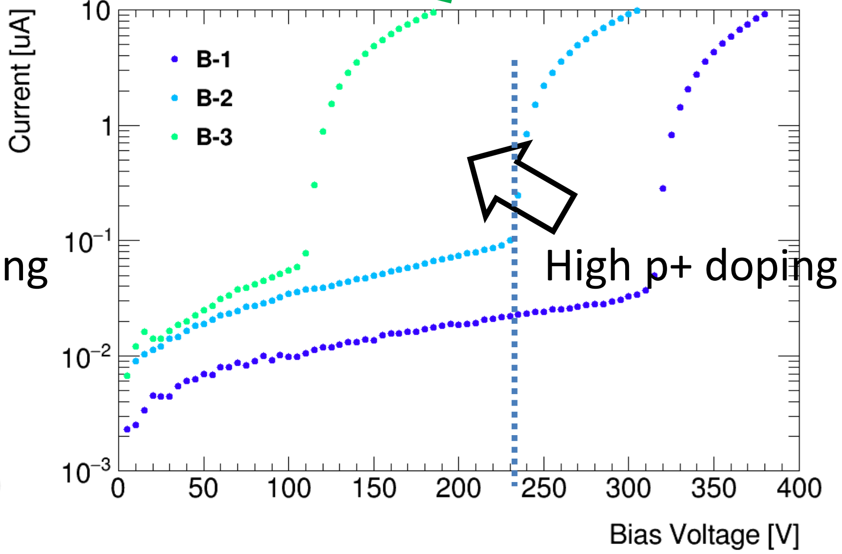
Higher Gain/earlier break in case :

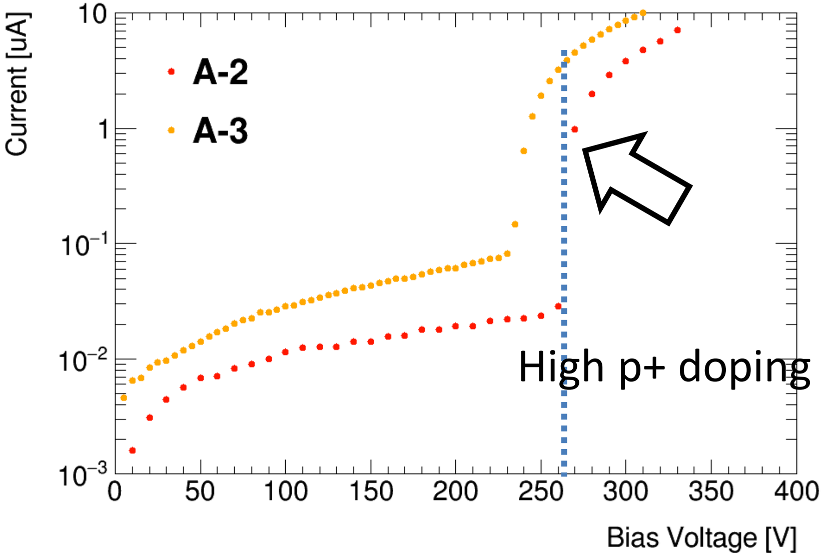
- Higher p+ doping
- Lower n+ doping

C-2 type should be :

- Smaller crosstalk
- Relatively higher gain

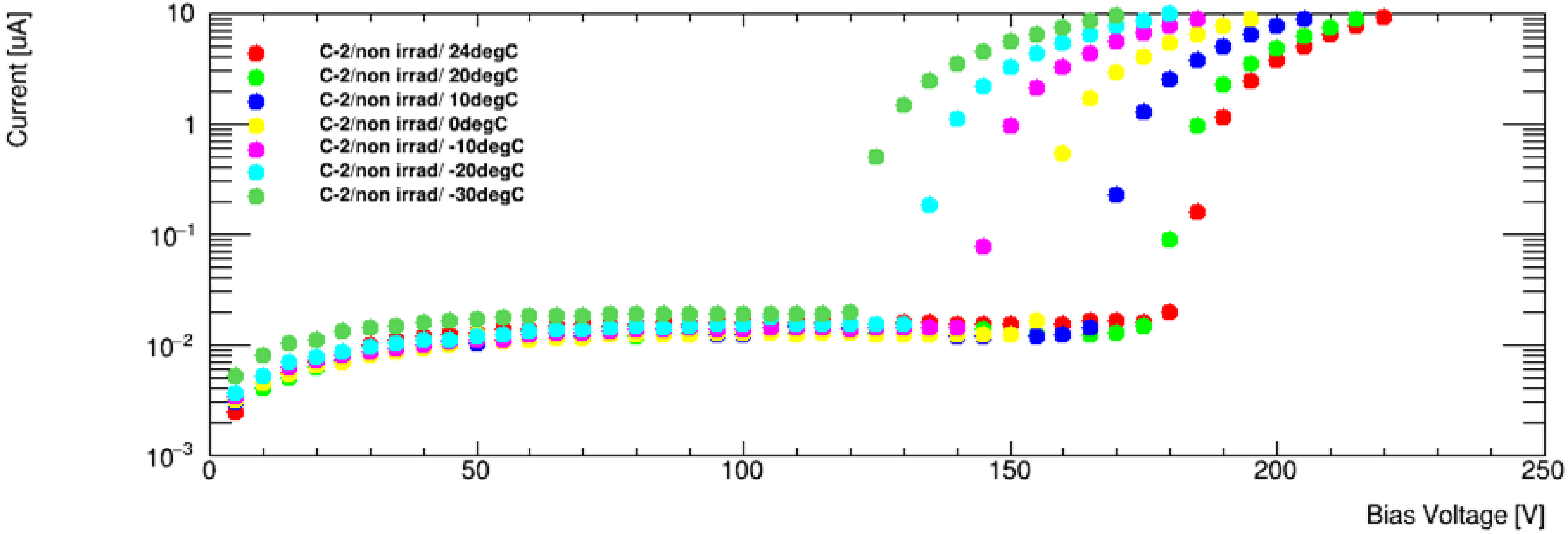






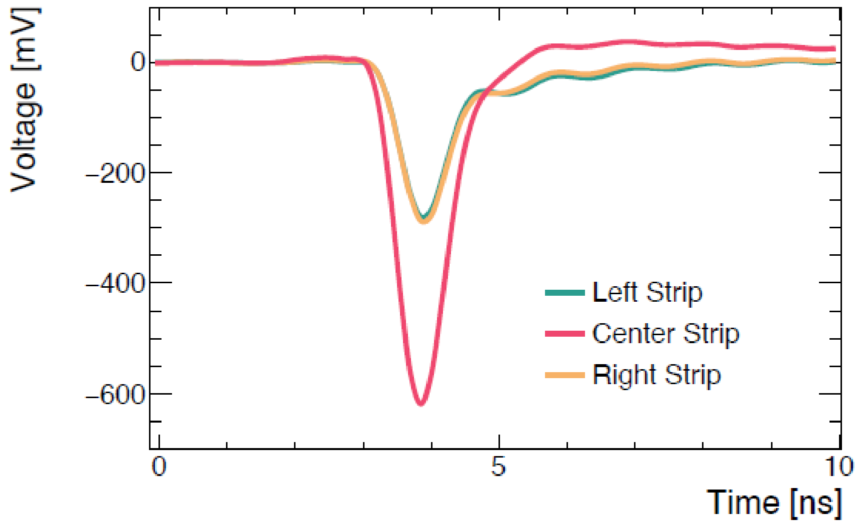
Temperature dependent IV curve

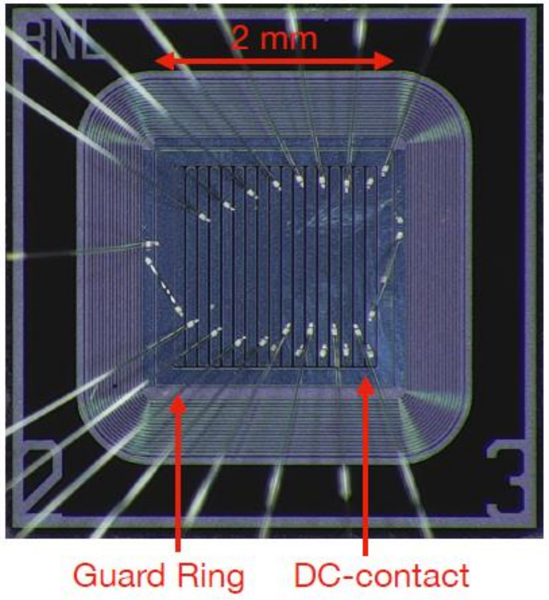
- Changed temperature from -30^{o}C to 24^{o}C



(参考)BNLのセンサー

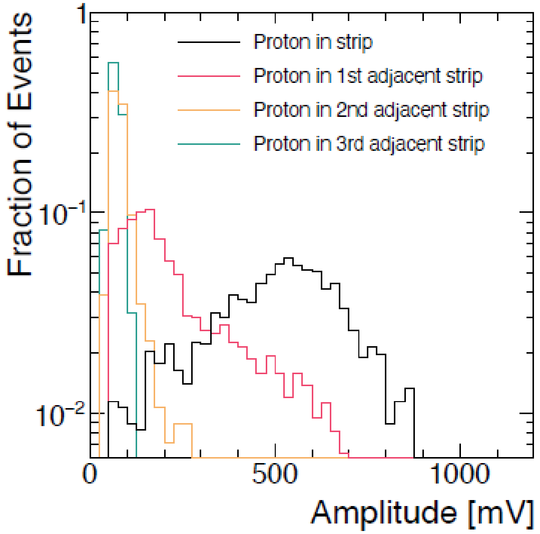
- Fabricated at BNL
  - 50 μm thick p- substrate
  - Depletion voltage -150 V
  - Breakdown -225 V at 22C
  - Bias Voltage -210 V
- 17 Strips
  - 100 μm pitch
  - 80 μm width
- DC contact surrounds pads
  - behaves as a standard LGAD when directly traversed by a proton
  - used to measure gain
- Readout with Fermilab 16-channel board
  - 15 strips (additional stage of amplification)
  - DC pad





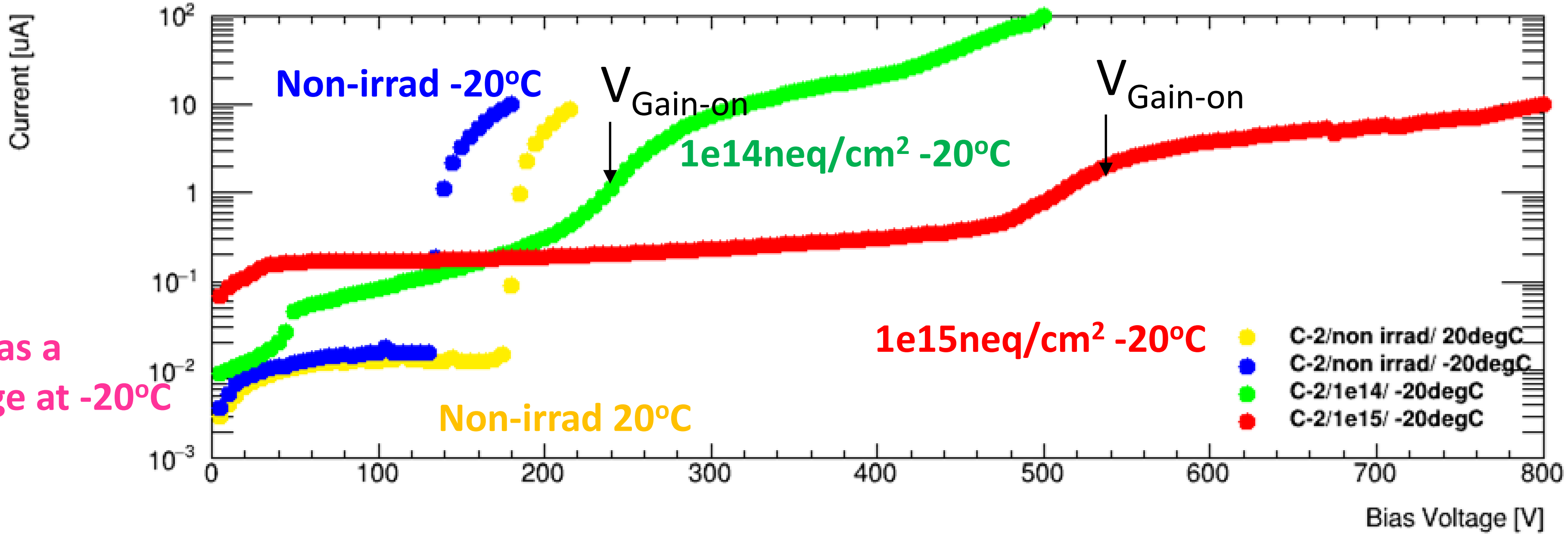
N+ 濃度が1e17/cm^3程度
→ DCLGADの1/100

Amplitude distributions
for different proton positions



Electrical test after Irradiation

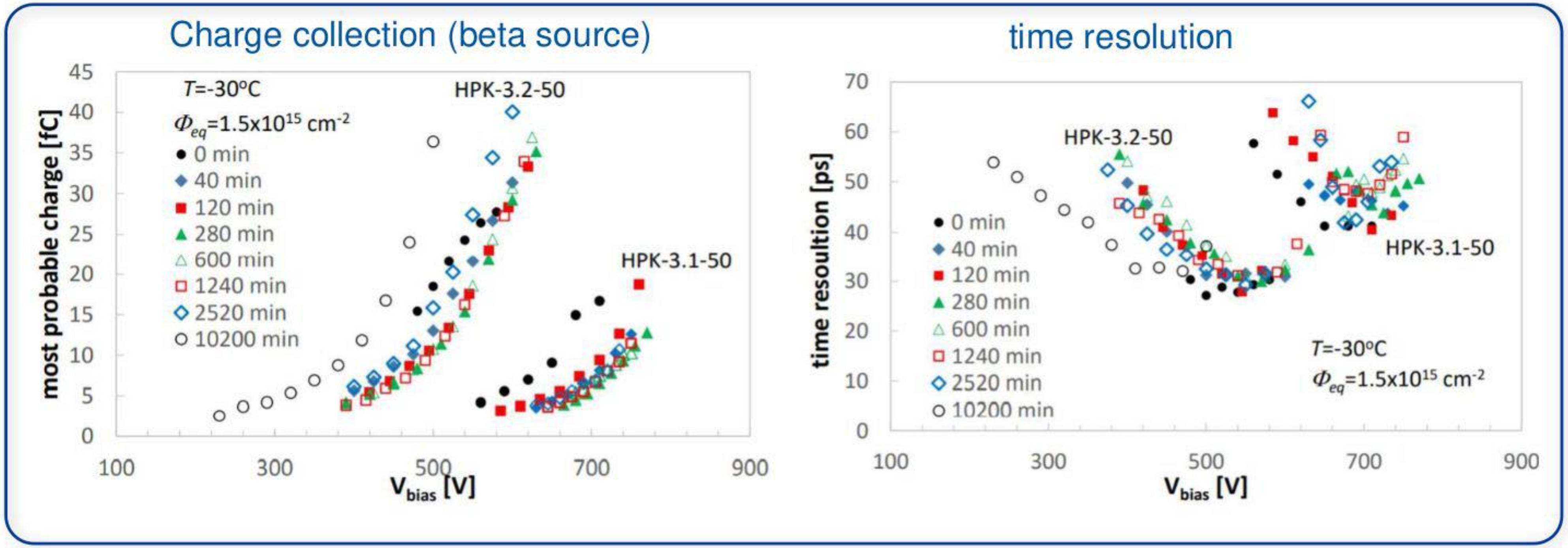
- Irradiated sensors at 1e14neq/cm^2 and 1e15neq/cm^2 and tested I-V performance.
- Gain-on voltage increased to **~220V @ 1e14neq/cm^2** and **550V @ 1e15neq/cm^2** ; they still seem to have gain.



Note: Non-irrad sample has a lower gain-on voltage at -20°C 190V→140V

ATLAS/CMSの結果 @ Vertex 2020

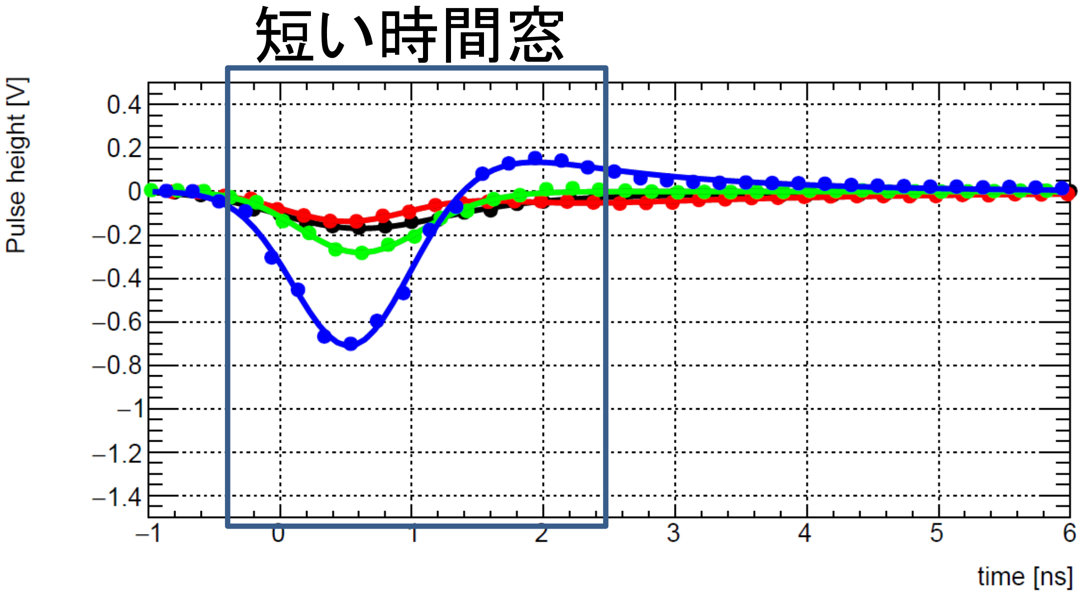
- DC-LGAD(ATLAS/CMS run)の結果
  - 1.5e15 neq/cm^{2}の時増幅が出るのは約500-600V
- 前のページの結果とさほど違いはない。
  - →n+濃度を薄くすることによる放射線耐性の悪化は見られないか？

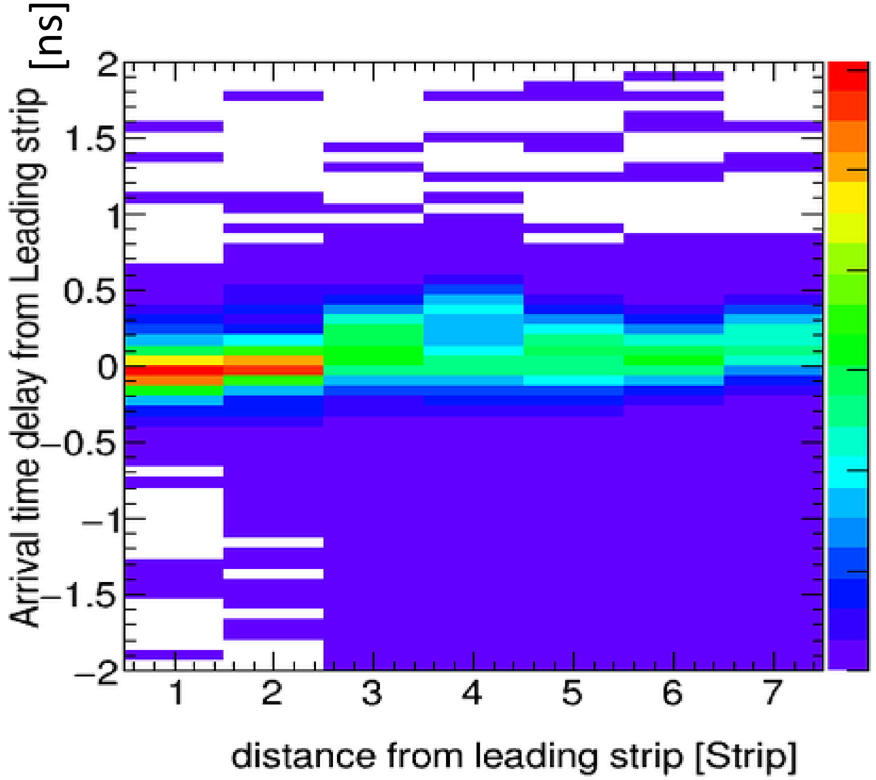


ポリシリコンの必要性(?)

- BNLのサンプルで、DCリングとバイアスリング間の抵抗の有無でテストした結果があるそうです。
  - 短い時間窓を設定したときは基本的には結果は変わらないとのこと。
  - ただし、信号の伝達速度は8 strip (640um)で<100ps なので反射があると影響があるか？

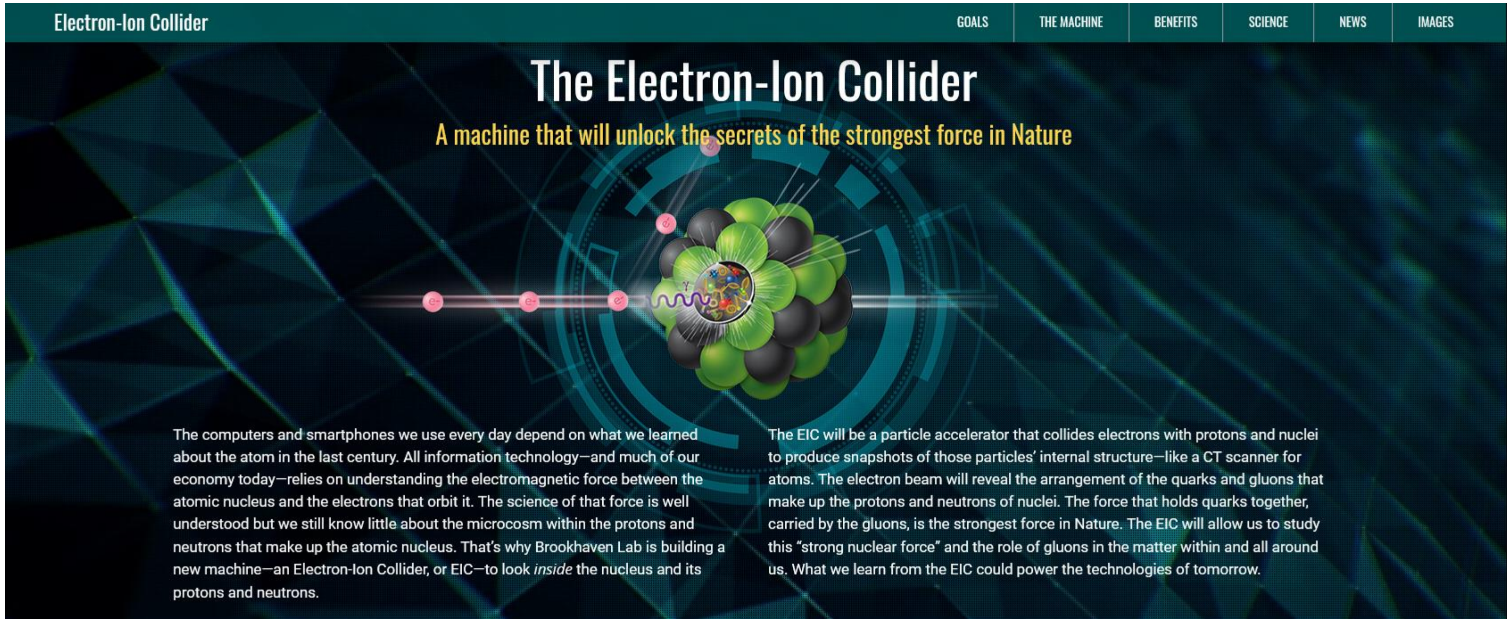
可能なら、一枚ポリシリなしのwaferをプロセスしてもらえますでしょうか。





余談

- FBK, BNL, HPKのAC-LGADが**位置分解能、時間分解能をあわせもち、不感領域もない**ということもあって、将来の加速器に使おうという動きが欧米で進んでいます。
  - 将来的にはATLASのような大型ハドロン衝突型加速器に入れたいところですが、計画、建設、実験開始と非常に長い時間を要します。(2040年以降)
  - アメリカに建設予定の**電子・イオン衝突実験でACLGADを実現しようというコンソーシアム**がアメリカを中心に盛り上がっています。これが実現すると10年後にATLASと同程度の飛跡検出器(StripやPixelの部分)全体にAC-LGADを入れる可能性もあります。→ 大型の(100-200m^2)量産になります。



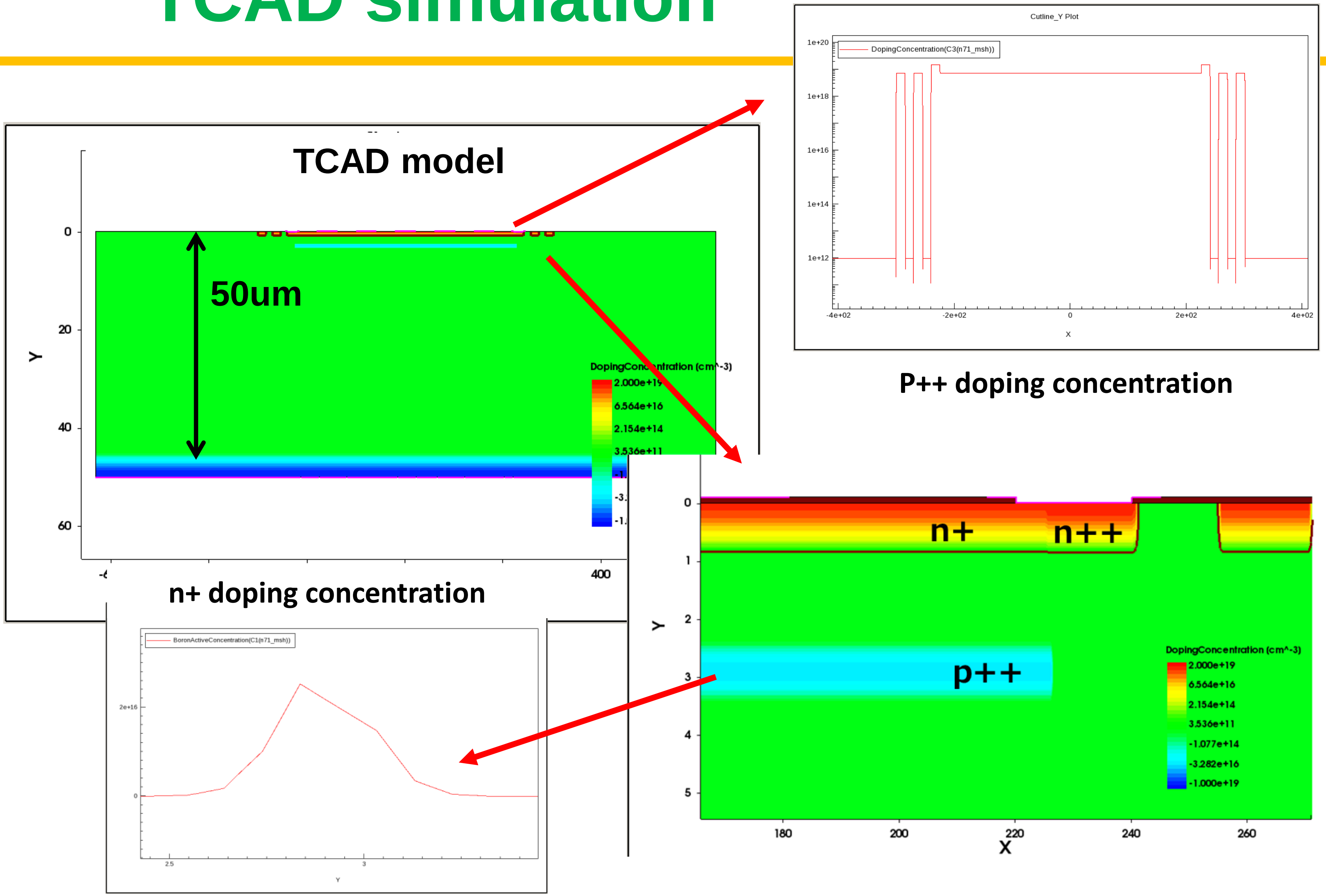
The Electron-Ion Collider

A machine that will unlock the secrets of the strongest force in Nature

The computers and smartphones we use every day depend on what we learned about the atom in the last century. All information technology—and much of our economy today—relies on understanding the electromagnetic force between the atomic nucleus and the electrons that orbit it. The science of that force is well understood but we still know little about the microcosm within the protons and neutrons that make up the atomic nucleus. That's why Brookhaven Lab is building a new machine—an Electron-Ion Collider, or EIC—to look *inside* the nucleus and its protons and neutrons.

The EIC will be a particle accelerator that collides electrons with protons and nuclei to produce snapshots of those particles' internal structure—like a CT scanner for atoms. The electron beam will reveal the arrangement of the quarks and gluons that make up the protons and neutrons of nuclei. The force that holds quarks together, carried by the gluons, is the strongest force in Nature. The EIC will allow us to study this "strong nuclear force" and the role of gluons in the matter within and all around us. What we learn from the EIC could power the technologies of tomorrow.

TCAD simulation

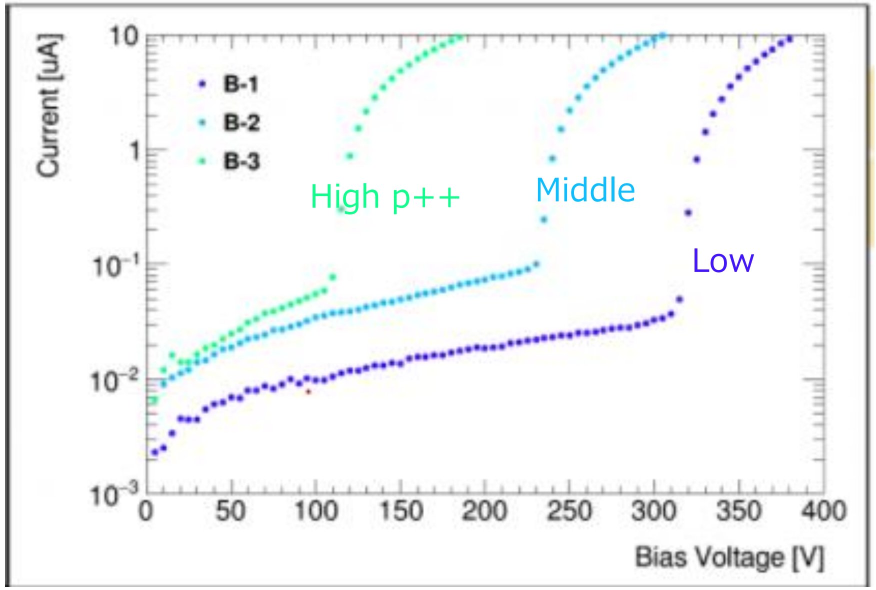


P++ doping concentration

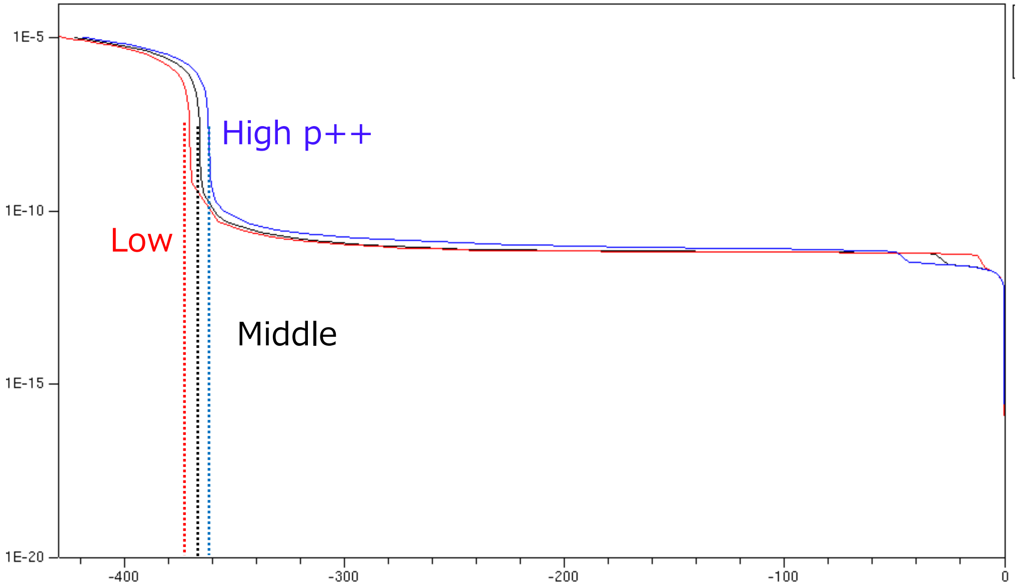
n+ doping concentration

TCAD simulation – IV curve

◆ Measurement



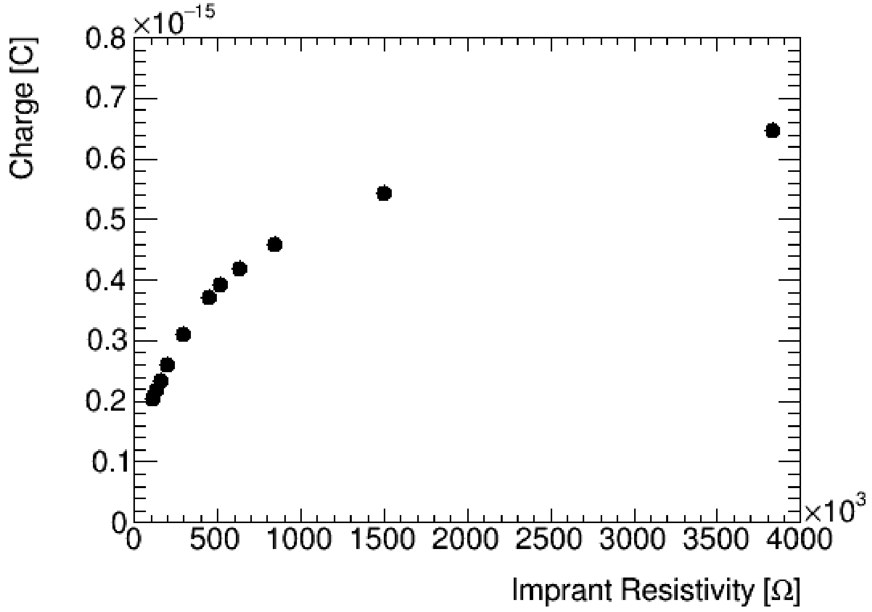
◆ Simulation



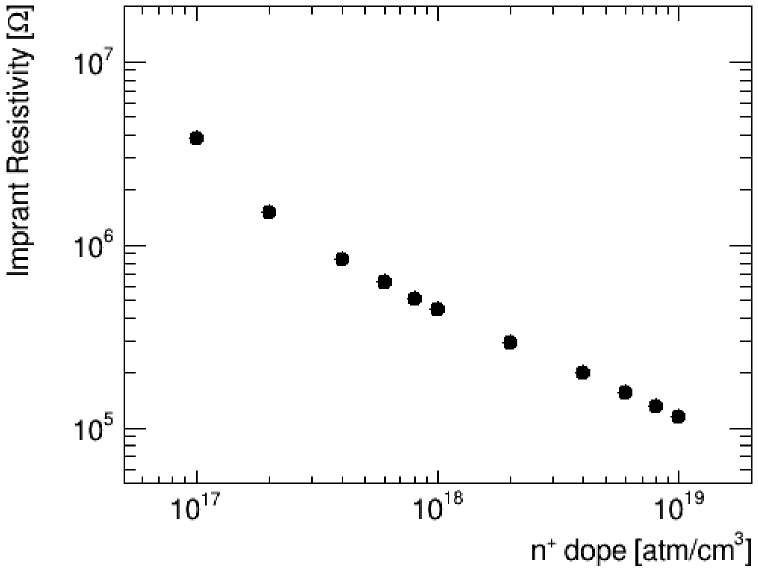
The higher the p++, the lower the voltage at which avalanche amplification occurs

- Signal size

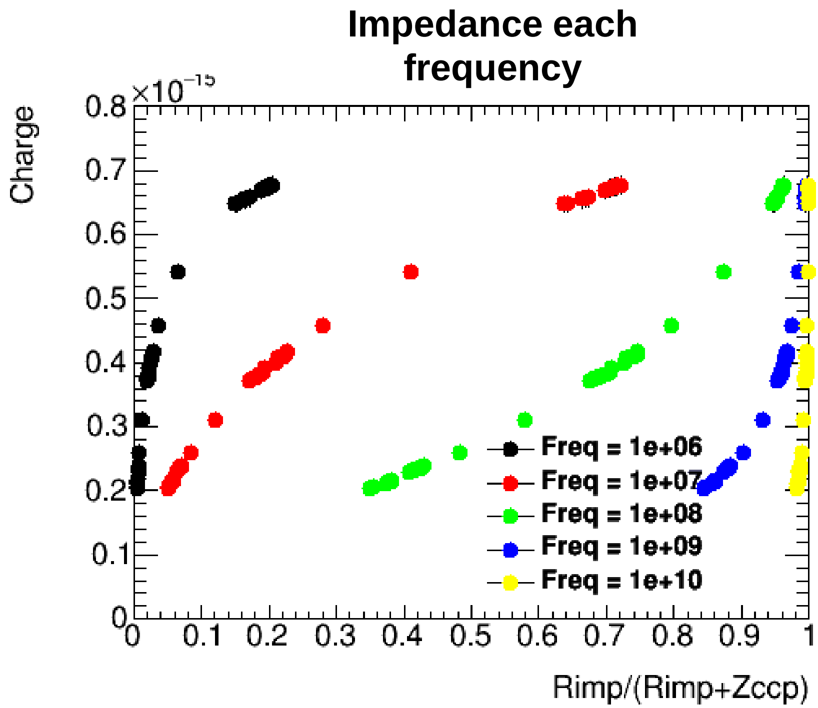
Simulation

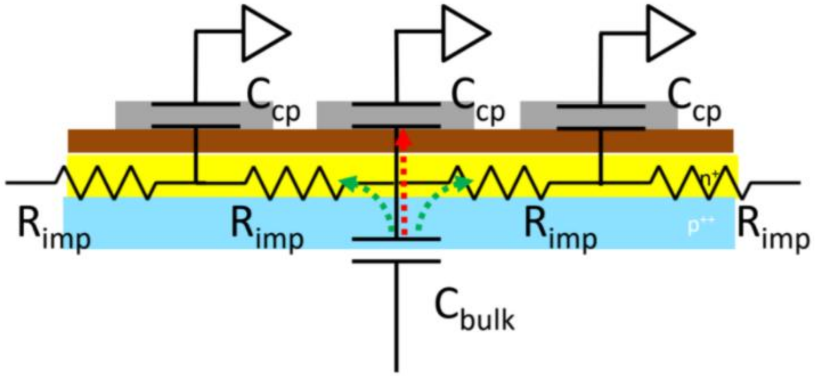


Implant resistivity vs n dope concentration



Frequency dependence





$$Q = \frac{Z_{R_{imp}}}{Z_{R_{imp}} + Z_{C_{cp}}} Q_0 = \frac{R_{imp}}{R_{imp} + 1/2\pi f C_{cp}}$$

From this equation, readout charge Q should be propositional to the Rimp/(Rimp+Zcp) and slope shoulbe Qo.

Frequency to calculate the impedance from capacitance is not sure (should be order of 100MHz since pulse shape have a few ns width) but probably the freqency value which makes that the readout charge proposional to the Rimp/(Rimp+Zcp) is actual value.

i.e. 10-100MHz from the plot.